Canada

Contractor's Report [1]
DSS Contract 41SS.KL229-1-4114

ENFOR Project C-172 (1)

A Workbook for Biomass Gasifier Sampling and Analysis

Contractor: Techwest Enterprises Ltd.
3650 Wesbrook Mall
Vancouver, B.C.
V6S 2L2

Scientific Authority:

Dr. D.P.C. Fung
Energy Research Laboratory
CANMET
Energy, Mines and Resources Canada
Ottawa, Ontario
K1A 0G1

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October 1983

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1.0 INTRODUCTION

Biomass gasifiers convert cellulosic solids to a gas which can be burned directly as a fuel, or can be converted to other products such as methanol and industrial chemicals. To calculate the efficiency of this conversion, it is necessary to measure the flow rate, composition and energy content of the various streams entering and leaving the gasifier system. Concurrent calculation of mass balances and energy balances allows an evaluation to be made of the accuracy of these measurements.

This workbook provides a methodology for the following procedures:

a. Obtaining an accurate sample of the raw producer gas. The components of this sample consist of:

   i. coarse particles and/or aerosols as they exist at the sampling temperature,

   ii. fine particles and those tars which condense at or above 200°C,

   iii. tars and aqueous condensate which condense between 200°C and 0°C.

   iv. noncondensable, dry producer gas.

b. Measuring the total flow rate of the gas streams entering and leaving the gasifier system. Alternately, these flows may be estimated using elemental mass balances.

c. Recovering and analyzing the components of the product stream for mass concentration, elemental composition and calorific value.

d. Using these data to calculate mass balances, energy balances, net conversion efficiency and gross conversion efficiency.

e. Analyzing the aqueous condensate for phenolics, organic acids, alcohols and other components.

f. Modifying a commercial high volume stack sampler to enable it to sample the hot gases and tarry residues.

This workbook was prepared for ENFOR as a component of Project No. C-172. The development of the sampler using the B.C. Research fluidized bed gasifier is described in the document "Development of Sampling and Analytical Procedures for Biomass Gasifiers" (Aiken, 1983).* Application of this workbook methodology to sampling of the Forintek Canada Corporation's downdraft gasifier is described in the document "Testing the Prototype Sampler on a Downdraft Biomass Gasifier." (Aiken, 1983). Results of the analysis of tars collected from the B.C. Research and Forintek gasifiers are presented in the final report for the project (McDonald, 1983).

Section 2 discusses the basic requirements for element mass balances, energy balance and energy conversion efficiency calculations.

Section 3 outlines the data required for the mass and energy balance calculations.

* This report is not available for general distribution. However, sampling and analytical procedures are described in the document "A Workbook for Biomass Gasifier Sampling and Analysis" which is available upon request from the ENFOR Secretariat.

Section 4 describes the apparatus and sampling procedures for obtaining the necessary samples.

Section 5 describes procedures for the analysis of input and output streams for elemental composition and calorific value.

Section 6 outlines the calculations required for mass and energy balances, including the process for estimating gasifier system heat losses. Worksheets are provided in the Appendices for stack calculations and mass and energy balance calculations.

Section 7 describes procedures for calibrating the gasifier sampler components.

2.0 GASIFIER PERFORMANCE

Performance criteria for a biomass gasifier are based on either the degree of conversion of biomass feed to valuable end products or the energy conversion efficiency. In either case the flow rate and composition of streams entering and leaving the gasifier system must be known. To ascertain the accuracy of sampling and analytical procedures it is necessary to calculate element and total mass balances around the gasifier system. Energy balances, on the other hand, allow an assessment of energy losses from the gasifier system and calculation of the energy conversion efficiency.

Gasifier input and output mass and energy flows are shown schematically in Figure 1. Also shown are typical parameters to be measured and their units. Since gasifier configurations vary appreciably between units, it may be necessary to delete streams or to add streams. The number and type of streams will vary depending on where the system envelope is drawn. Internally recycled streams, such as the cyclone char recycle, are usually kept within the envelope unless the performance of the gasifier reactor itself is being measured.

2.1 Mass Balances

Mass balance calculations are based on two premises:

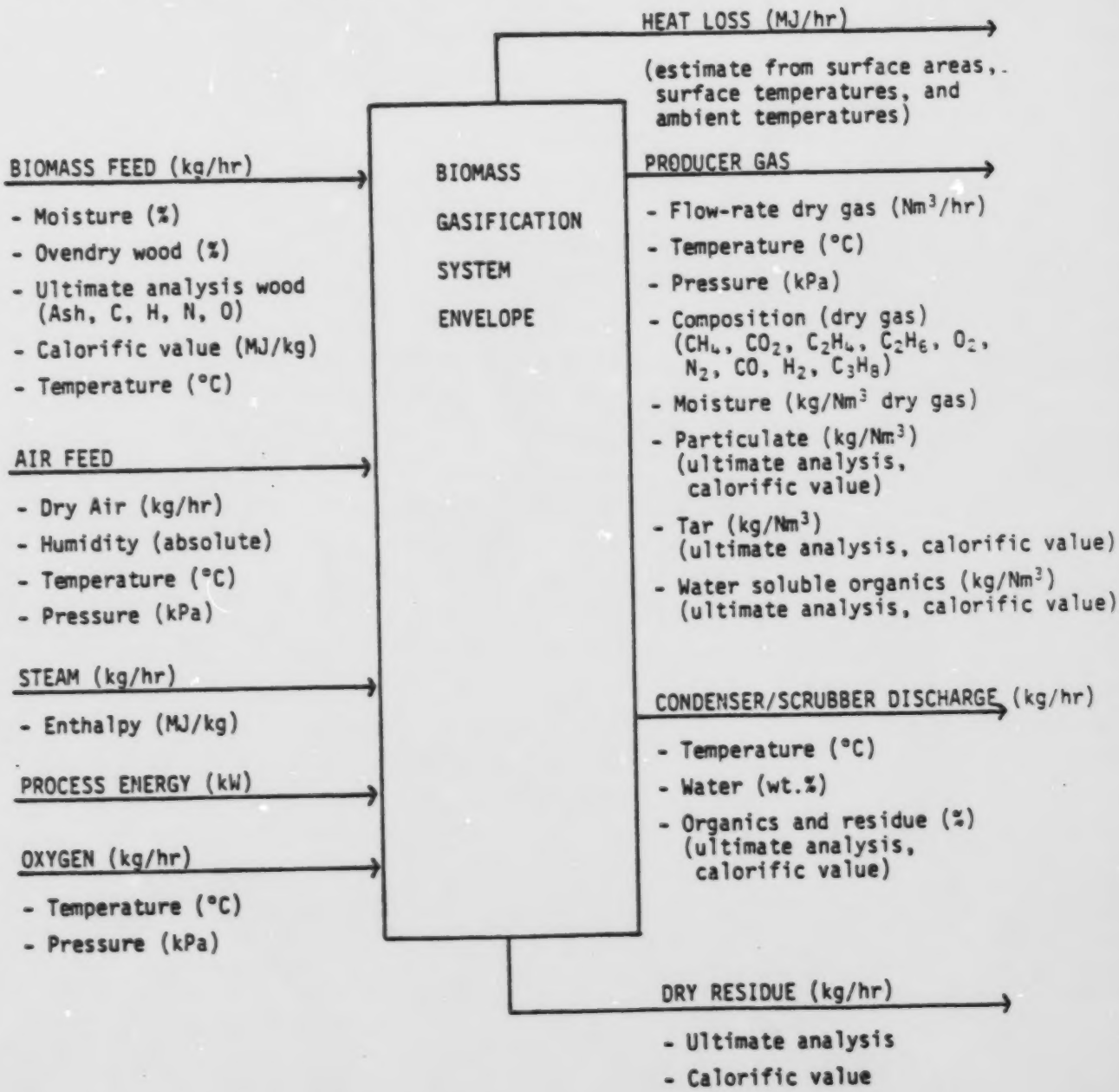
a. The gasifier operation is steady-state so that the total flowrate of mass entering the system envelope equals the total flowrate of mass leaving the system envelope.

b. Transmutation of elements does not occur - the rate at which each element enters the gasifier system equals the rate at which the element leaves the system.

FIGURE 1

GASIFIER MASS AND ENERGY STREAMS

- Not all streams will be present on all gasifiers
- Gas flow and enthalpies at 15°C, 1 atm.
- Nm^3 is the volume in m^3 at standard conditions, 15°C, 1 atm.


HEAT LOSS (MJ/hr)
(estimate from surface areas, surface temperatures, and ambient temperatures)
BIOMASS FEED (kg/hr)
- Moisture (%)
- Ovendry wood (%)
- Ultimate analysis wood (Ash, C, H, N, O)
- Calorific value (MJ/kg)
- Temperature (°C)
AIR FEED
- Dry Air (kg/hr)
- Humidity (absolute)
- Temperature (°C)
- Pressure (kPa)
STEAM (kg/hr)
- Enthalpy (MJ/kg)
PROCESS ENERGY (kW)
OXYGEN (kg/hr)
- Temperature (°C)
- Pressure (kPa)
BIOMASS GASIFICATION SYSTEM ENVELOPE
PRODUCER GAS
- Flow-rate dry gas (Nm^3/hr)
- Temperature (°C)
- Pressure (kPa)
- Composition (dry gas) (CH_4, CO_2, C_2H_4, C_2H_6, O_2, N_2, CO, H_2, C_3H_8)
- Moisture (kg/Nm^3 dry gas)
- Particulate (kg/Nm^3) (ultimate analysis, calorific value)
- Tar (kg/Nm^3) (ultimate analysis, calorific value)
- Water soluble organics (kg/Nm^3) (ultimate analysis, calorific value)
CONDENSER/SCRUBBER DISCHARGE (kg/hr)
- Temperature (°C)
- Water (wt.%)
- Organics and residue (%) (ultimate analysis, calorific value)
DRY RESIDUE (kg/hr)
- Ultimate analysis
- Calorific value

2.2 Energy Balances

Reference conditions of 15°C and one atmosphere are used for the energy balances, in accordance with ISO 5024 (ISO, 1977).

The calculation of an energy balance, as per cent closure, allows an evaluation of the accuracy of measurements for all input and output sources of energy.

Two energy conversion efficiencies are calculated. The first, the gross efficiency, reflects the recoverable energy available to a process adjacent to a gasifier. The gross efficiency is defined as the recoverable energy of the raw producer gas divided by the total energy input, expressed as a percentage. The second, the net efficiency, gives the recoverable energy available to a distant process. The net efficiency is defined as the standard higher heat of combustion of the clean, dry gas divided by the total energy input, expressed as a percentage.

To determine these energy balances, calculations of heats of combustion, sensible and latent heats, enthalpy of water, electro-mechanical energy and process heat loss are necessary.

The following Section lists the data that will be required for computing mass and engery balances.

A discussion of the actual methodology of calculation is given in Section 6. "Fill-in-the-blanks" worksheets are presented in Appendices F and G.

3.0 DATA REQUIREMENTS

The calculation of mass and energy balances requires data from three sources:

a. Gasifier operation
b. Source testing
c. Sample analysis

3.1 Gasifier Operation

Accurate measurements of either mass or volume flow rates are required for all input and output streams of the gasifier. Inflow streams, such as feed, air, steam and water, must be identified and accurately measured.

Data required of the gasifier operation include:

a. Type and number of input feed streams.
b. Mass flowrates of feed streams.
c. Mass flowrate of input air.
d. Mass flowrates of other input streams, such as steam and oxygen.
e. Mass flowrates of nongaseous output streams, such as char.
f. Process energy inputs.
g. Operating data, such as reactor temperatures and pressures.
h. Temperature profile of exterior walls of gasifier as required for heat loss calculation.
i. Dry and wet bulb temperatures of ambient air.
j. Brief description and diagram of gasifier operation.

3.2 Source Testing

Source testing is the experimental process of determining the characteristics of a raw gas stream discharged from a combustion or other industrial process.

Data required from the source test include:

a. Mass fraction of water in the producer gas.
b. Molecular weight of the producer gas.
c. Volume flowrate of the producer gas.
d. Temperature and pressure of the producer gas.
e. Mass concentration of the gaseous components of the producer gas.
f. Mass concentrations of particulates, tars and water soluble organics in the producer gas.

3.3 Sample Analysis

Samples of the producer gas, particulates, tars and condensate are obtained from the gasifier sampling train. Sampling of solid input and output streams for analysis must be carried out so that representative samples are collected. For example, feed samples must be sufficient in both size and number to account for variations in biomass composition and moisture content.

Data required from the sample analyses include:

a. Composition of the clean, dry producer gas as per cent by volume of hydrogen, carbon dioxide, methane, ethane, ethylene, carbon monoxide, nitrogen and oxygen. Higher hydrocarbons can be determined if required.

b. Weight, calorific value and carbon, hydrogen, nitrogen and oxygen contents of particulates.

c. Weight, water content, calorific value and carbon, hydrogen, nitrogen and oxygen contents of tars.

d. Volume and density of condensate.

e. Calorific value and carbon, hydrogen, nitrogen, and oxygen contents of water soluble organics in condensate.

f. Moisture content, calorific values and carbon, hydrogen, nitrogen and oxygen contents of feed and output streams, such as char.

4.0 SAMPLING METHODOLOGY

4.1 Sampler Design

The characteristics of raw producer gas from biomass gasification are such that conventional stack sampling equipment and procedures are less than ideal for obtaining representative samples. The gasifier sampler, shown in Figures 2 and 3, is a precision instrument capable of sampling particulate and gaseous emissions from biomass gasifiers, in accordance with the requirements and regulations of the Federal Environmental Protection Service. EPS Report No. 1-AP-74-1 describing these regulations is included as Appendix A.

The gasifier sampler has several unique features that allow accurate sampling of the high temperature gases and tarry residues found in raw producer gas. These features, shown schematically in Figure 2 include:

a. The probe and cylcone are heated to approximately the same temperature as the stack to prevent condensation of tarry residues in the probe.

b. The gas sample is passed through a forced convection heat exchanger coil where the temperature is raised or lowered to a standard value of 200°C. Higher temperatures can cause thermal cracking of deposited particulates and tars and breakdown of the fibreglass filter. Lower temperatures can result in tar buildup on the filter, which would rapidly plug tne filter and reduce the sampling flow rate.

FIGURE 2

GASIFIER SAMPLING TRAIN
(SCHEMATIC)

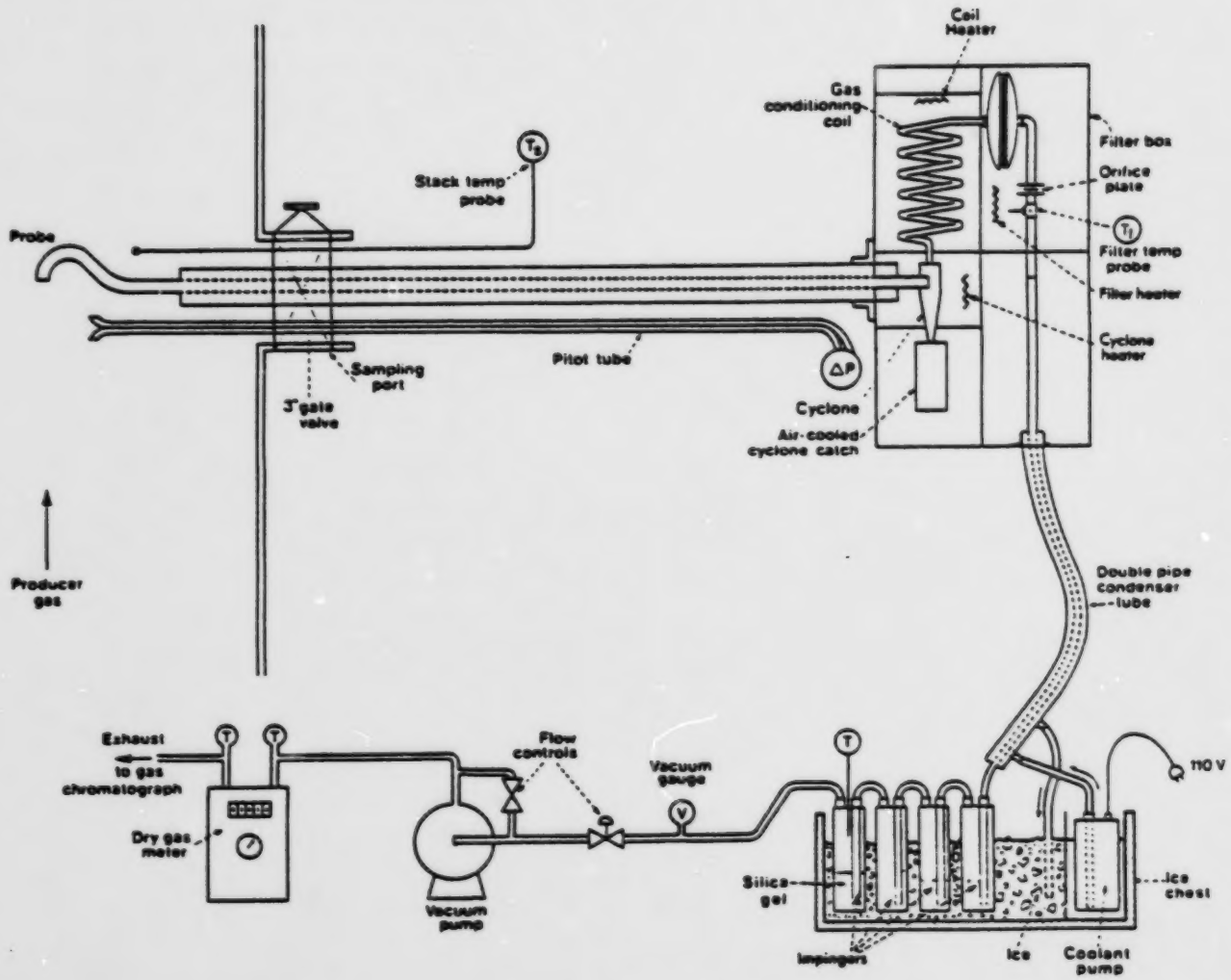
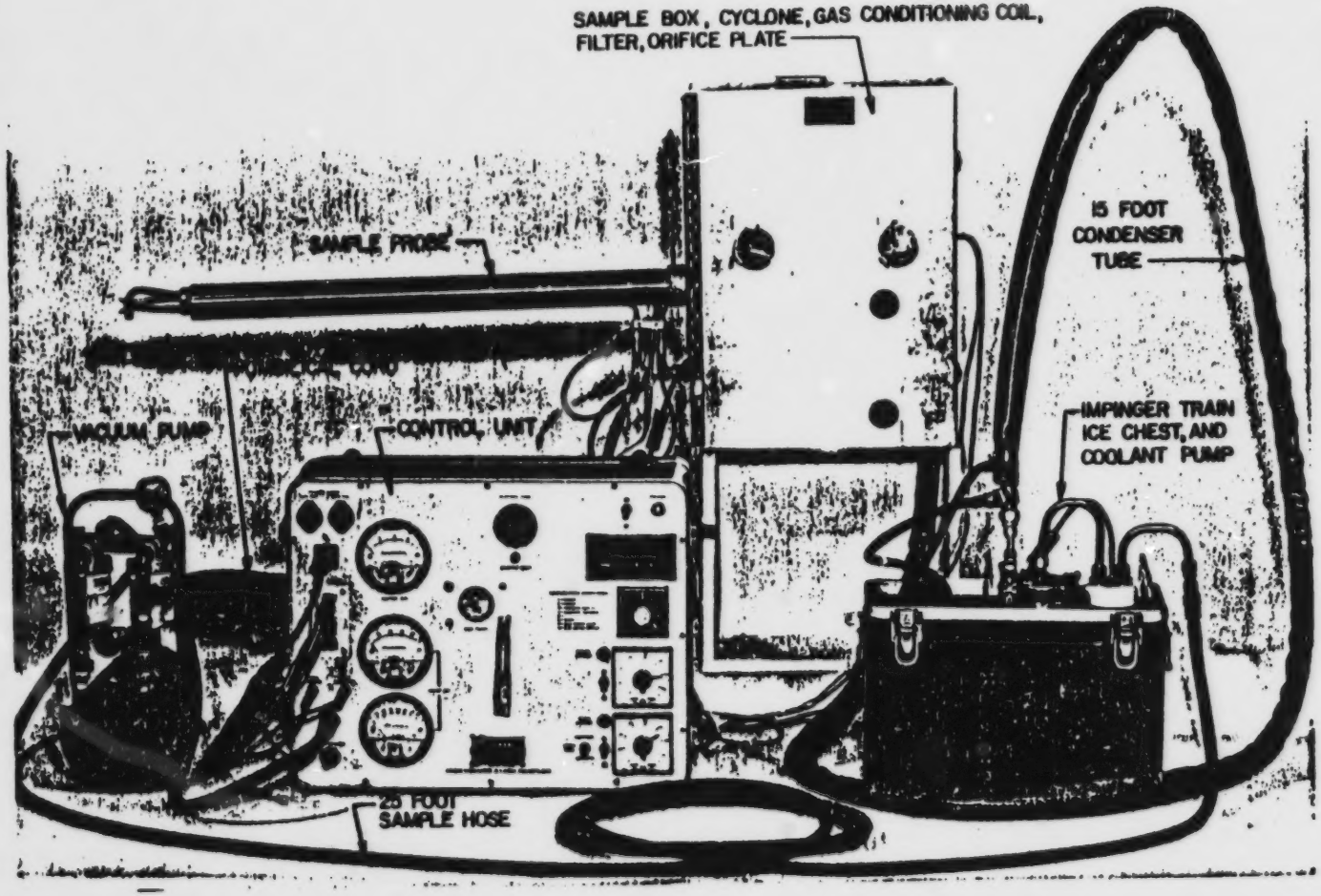


FIGURE 3

GASIFIER SAMPLER

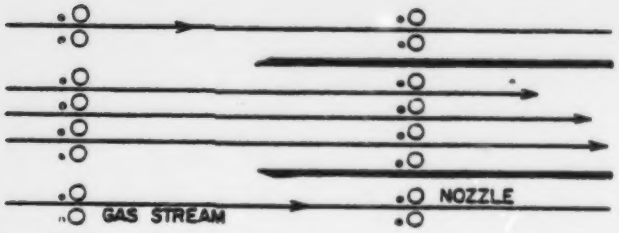

SAMPLE BOX, CYCLONE, GAS CONDITIONING COIL, FILTER, ORIFICE PLATE
15 FOOT CONDENSER TUBE
SAMPLE PROBE
VACUUM PUMP
CONTROL UNIT
IMPINGER TRAIN ICE CHEST, AND COOLANT PUMP
25 FOOT SAMPLE HOSE

c. The sampling-rate orifice is placed in the sample box immediately after the filter assembly and thus is kept at the filtering temperature of 200°C. Hence, a knowledge of producer gas composition and moisture content is not required prior to a run, and isokinetic sampling can proceed without exploratory tests. Isokinetic sampling occurs when the linear velocity of the gas entering the sampling nozzle matches that of the undisturbed gas stream at the sampling location. Figure 4 shows that super-isokinetic sampling occurs when the nozzle velocity of the gas sample exceeds the stack gas velocity, resulting in lower grain loadings and particulate emissions. Sub-isokinetic sampling occurs when the nozzle velocity of the gas sample is less than the stack gas velocity, resulting in higher grain loadings and particulate emissions.

d. The gas leaving the orifice plate assembly at a temperature of 200°C is quenched immediately to about 0°C. This is accomplished in a unique counter-current heat exchanger/condenser which also acts as the sample line to the impinger assembly. Rapid heat exchange is accomplished by counter-current ice water circulation in the Teflon double pipe condenser tube. Tar and water condense in the inner Teflon sample tube. Condensate then flows by gravity to the impinger assembly while noncondensable gases pass through the impinger train to the conventional vacuum pump and control unit. At the design flow of 30 standard dry litres/min (1 cfm) a conventional ice-cooled impinger train would be unable to remove the sensible and latent heat present in the gas stream.

FIGURE 4

GAS FLOW ISOKINETICS



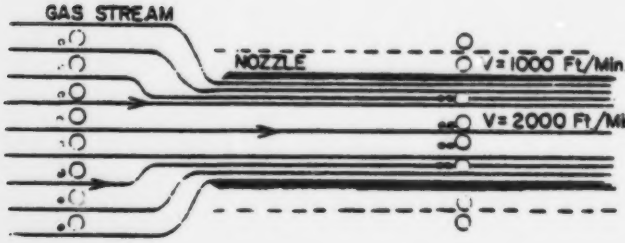
100% ISOKINETIC

$V_n = V_s$

$M_n = (4 \times 5 + 4 \times 1)$

$Q_n = 1$ cfm

$C_n = \frac{24}{1} = 24$



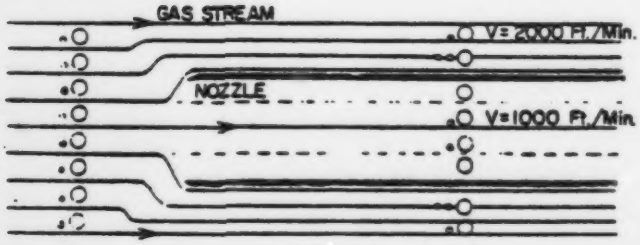
200 % ISOKINETIC

$V_n = 2V_s$

$M_n = (4 \times 5 + 8 \times 1)$

$Q_n = 2$ cfm

$C_n = \frac{28}{2} = 14$



50% ISOKINETIC

$V_n = 1/2\ V_s$

$M_n = (4 \times 5 + 2 \times 1)$

$Q_n = .5$ cfm

$C_n = \frac{22}{.5} = 44$

NOMENCLATURE

V_n - NOZZLE GAS VELOCITY, fpm

V_s - STACK GAS VELOCITY, fpm

M_n - NOZZLE PARTICULATE MASS, grain

Q_n - NOZZLE GAS VOLUME, cfm

C_n - NOZZLE PARTICULATE CONCENTRATION gr/cf

ISOKINECITY

AS SHOWN IN THE ABOVE DRAWINGS THE DEGREE OF ISOKINECITY IS DETERMINED BY THE NOZZLE VELOCITY IN RELATION TO THE GAS STACK VELOCITY. WHEN A VELOCITY CHANGE IN GAS FLOW IS ENCOUNTERED SMALL PARTICLES, BECAUSE OF THEIR LOW INERTIA FOLLOW THE GAS STREAMLINES WHEREAS LARGE PARTICLES HAVING SIGNIFICANT INERTIA MOVE INDEPENDENTLY OF THE GAS FLOW STREAMLINES CAUSING CONCENTRATION BIAS IN THE SAMPLE.

During the sampling operation, the gas stream is drawn through a nozzle of known diameter, the probe and a miniature high efficiency cyclone, all heated to approximately the temperature of the stack gas. Large particulates are removed from the gas sample in the cyclone. The gas is cooled or heated in the gas conditioning coil to the reference temperature of 200°C used for the filter and orifice plate assemblies. Particulates and some tar are removed on the glassfibre filter. The gas flow rate is measured in the orifice plate assembly by pressure differential and is controlled by the coarse and fine controls on the vacuum pump. Water, tar and water soluble organic compounds condense as the gas passes through the condenser tube and into the impinger assembly. As the gas stream passes through the impinger train, these condensable materials are trapped by water in the impingers. Moisture and trace amounts of tar in the gas stream are removed by silica gel in the fourth impinger. The gas stream passes through the vacuum pump and the dry gas meter in the control unit where the sample volume is measured. Dry, clean gas samples are taken at the dry gas meter discharge port using sample bags or glass sampling bombs. A detailed description of the sampling operation is given in Section 4.5.

4.2 Apparatus

The description of the sampler apparatus refers to components from an Aerotherm sampling train. Components from other commercial sampling trains which fulfill the same functions and requirements are acceptable.

4.2.1 Probe

An Aerotherm sample probe is modified to allow its use at temperatures as high as 800°C. A high temperature heating tape, two high temperature thermocouples and ceramic rope insulation are substituted for the normal components of the Aerotherm probe. A 312 watt, 1/2 inch Thermolyne Briskheat flexible heating tape with heavy Fibrox fibres is wrapped around the probe. The tape is further insulated with 1/4 inch ceramic fibre rope which has a continuous use limit of 1260°C.

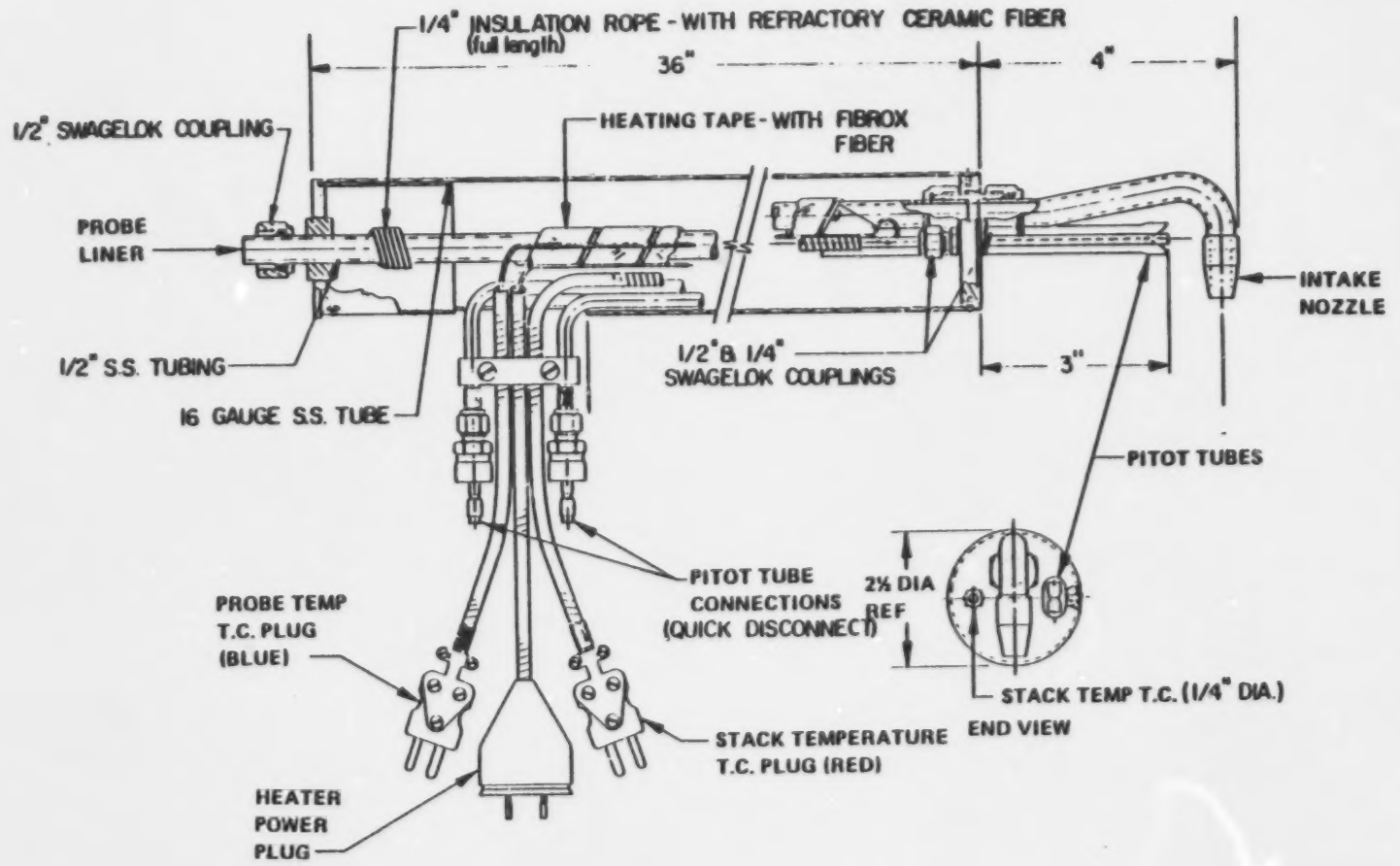
The probe assembly, shown in Figures 5 and 6, includes an outer 2 1/2 inch O.D. stainless steel shell, an S-type pitot tube, a 1/2 inch O.D. stainless steel liner, insulated heating tape and stack gas and probe temperature type K thermocouples. Interchangeable stainless steel nozzles (1/4 to 3/4 inch diameter) are attached to the probe using Swagelok connections. Quick disconnect fittings between the probe, sample box and umbilical line allow fast, easy connections.

4.2.2 Gate valve and spool assembly

The gate valve and spool assembly is shown in Figure 7. A standard 3 inch diameter gate valve and a 3 inch diameter spool (8 inches in length) with standard 150 lb flanges are used to seal the probe assembly into the sample port. A standard 3 inch pipe nipple cap with a 2 5/8 inch I.D. bore, a stainless steel compression gasket and ceramic fibre rope are used to make a tight seal between the round probe body and the spool. This assembly prevents the escape of toxic gases from the sample port. It should be installed when the plant is not operating. A flange cap is added to the end of the spool when the sample port is not in use.

FIGURE 5

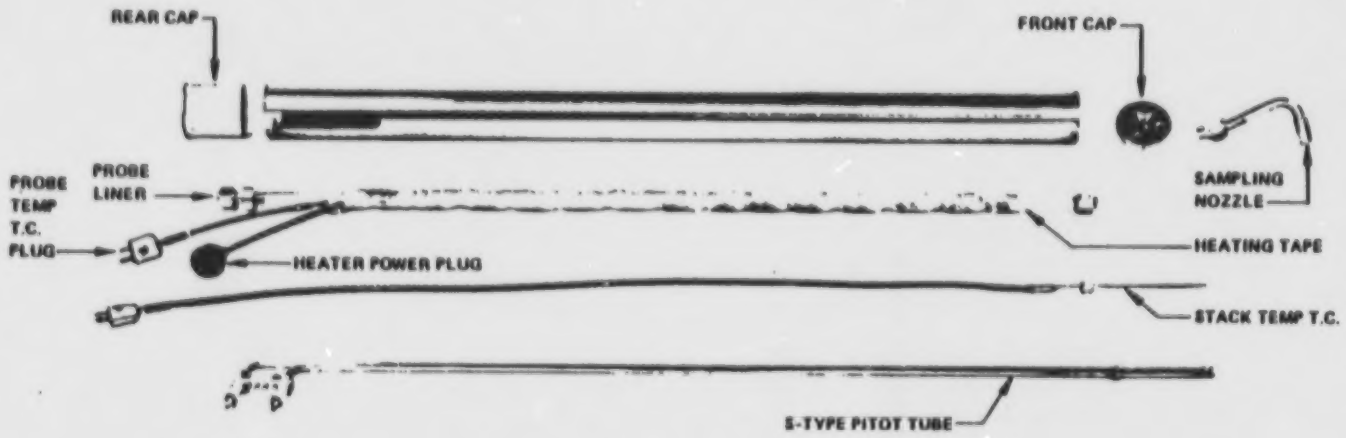
SAMPLE PROBE



Adapted from Aerotherm Manual

FIGURE 6

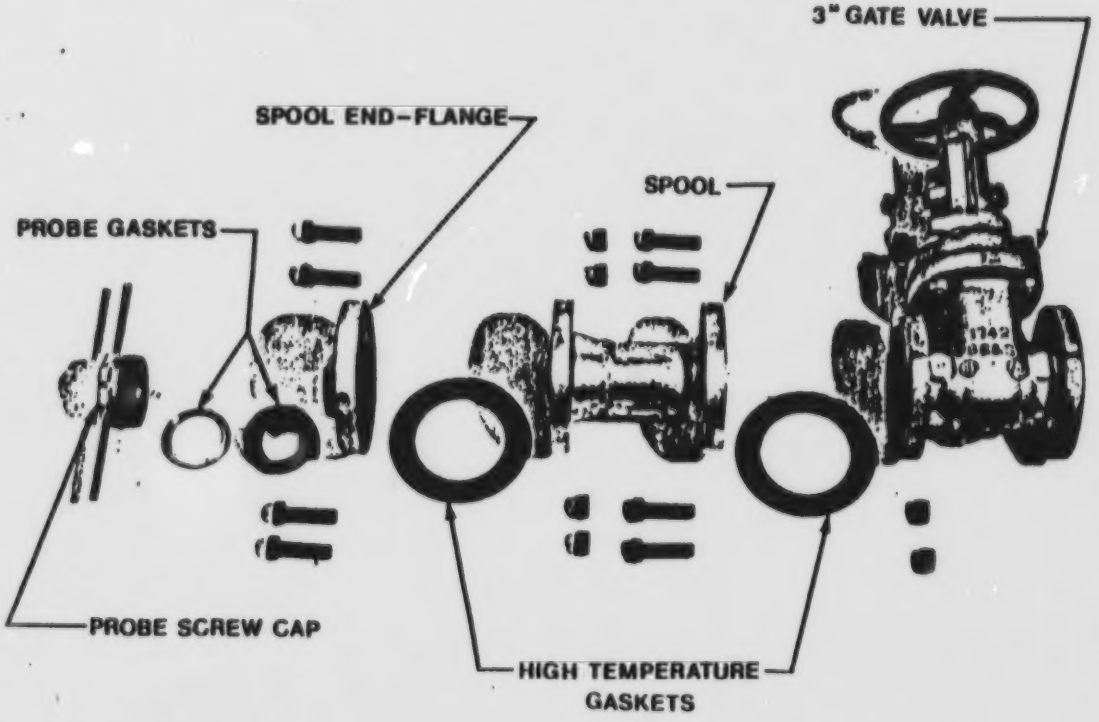
PROBE COMPONENTS



Reproduced from Aerotherm Manual

FIGURE 7

GATE VALVE-SPOOL ASSEMBLY



4.2.3 Sample box

The aluminum sample box, shown in Figure 8, supports the probe in alignment with the sample port and contains insulated temperature controlled compartments for the cyclone, coil, and filter and orifice plate assemblies. Each compartment is insulated with 1/2 inch Thermofrax duraboard which has a continuous use limit of 1260°C. The heaters and sensors required to maintain the temperatures of the cyclone, coil, filter and orifice plate are located in the box.

The squirrel cage blower mounted in the sample box serves two functions. First, it provides cooling air for the temperature controllers, switches, electrical connections and wiring which are located in a compartment at the back of the box. Second, the air is then blown over the heating element in the gas conditioning coil compartment, to facilitate uniform temperature control. The hot air exits through an adjustable vent in the compartment door.

The fan in the filter and orifice plate compartment provides air circulation to maintain a uniform temperature.

Individual components in the sample box are connected by Swagelok fittings, in the arrangement shown in Figure 8. These components are:

a. Cyclone - the stainless steel miniature high efficiency cyclone, shown in Figure 9, has a removable 250 mL stainless steel jar which is air cooled. A Teflon gasket and clamp are used to seal the collection jar to the cyclone. A threaded plug allows the cyclone to be removed for sample recovery.

FIGURE 8
SAMPLE BOX

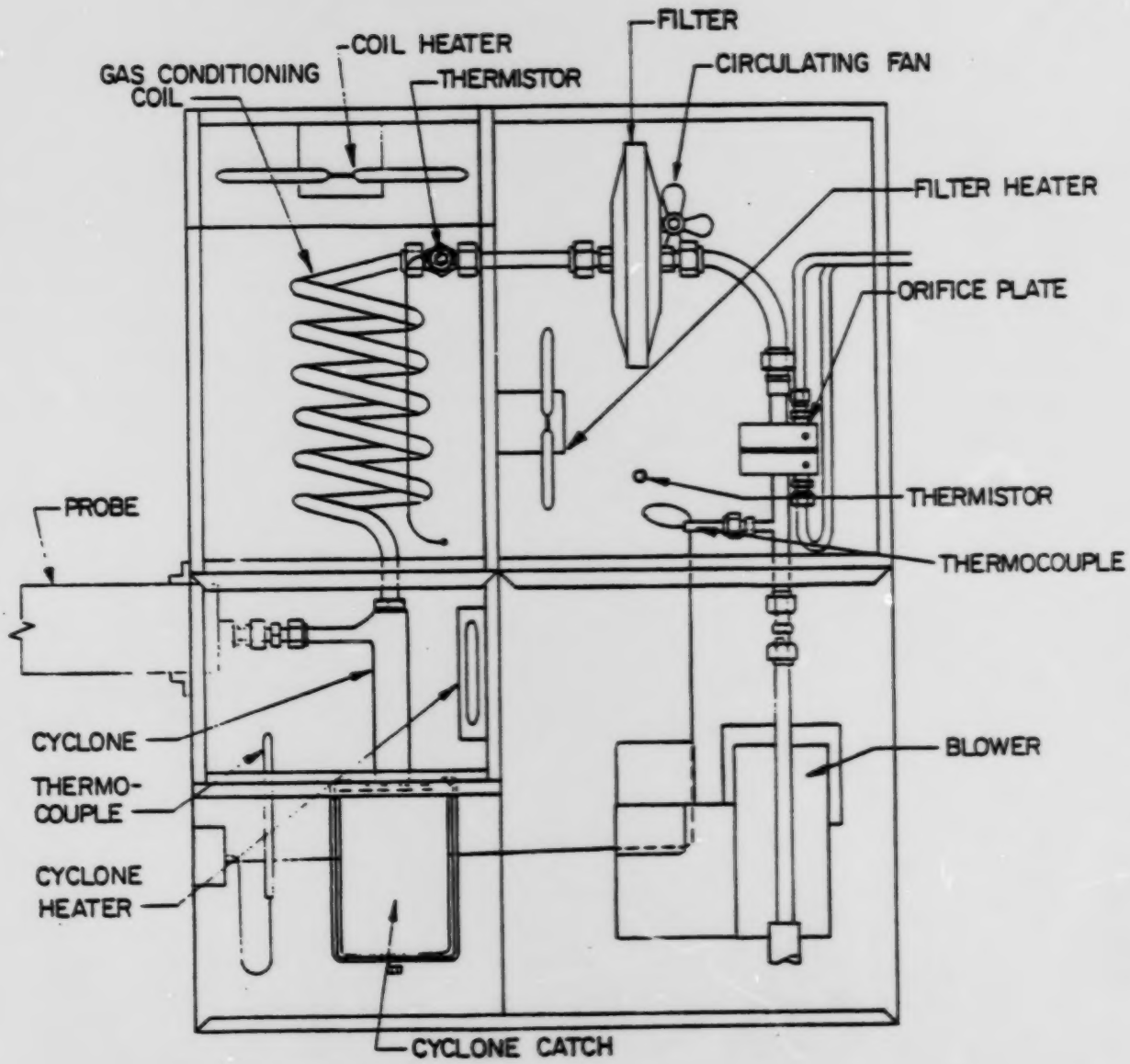
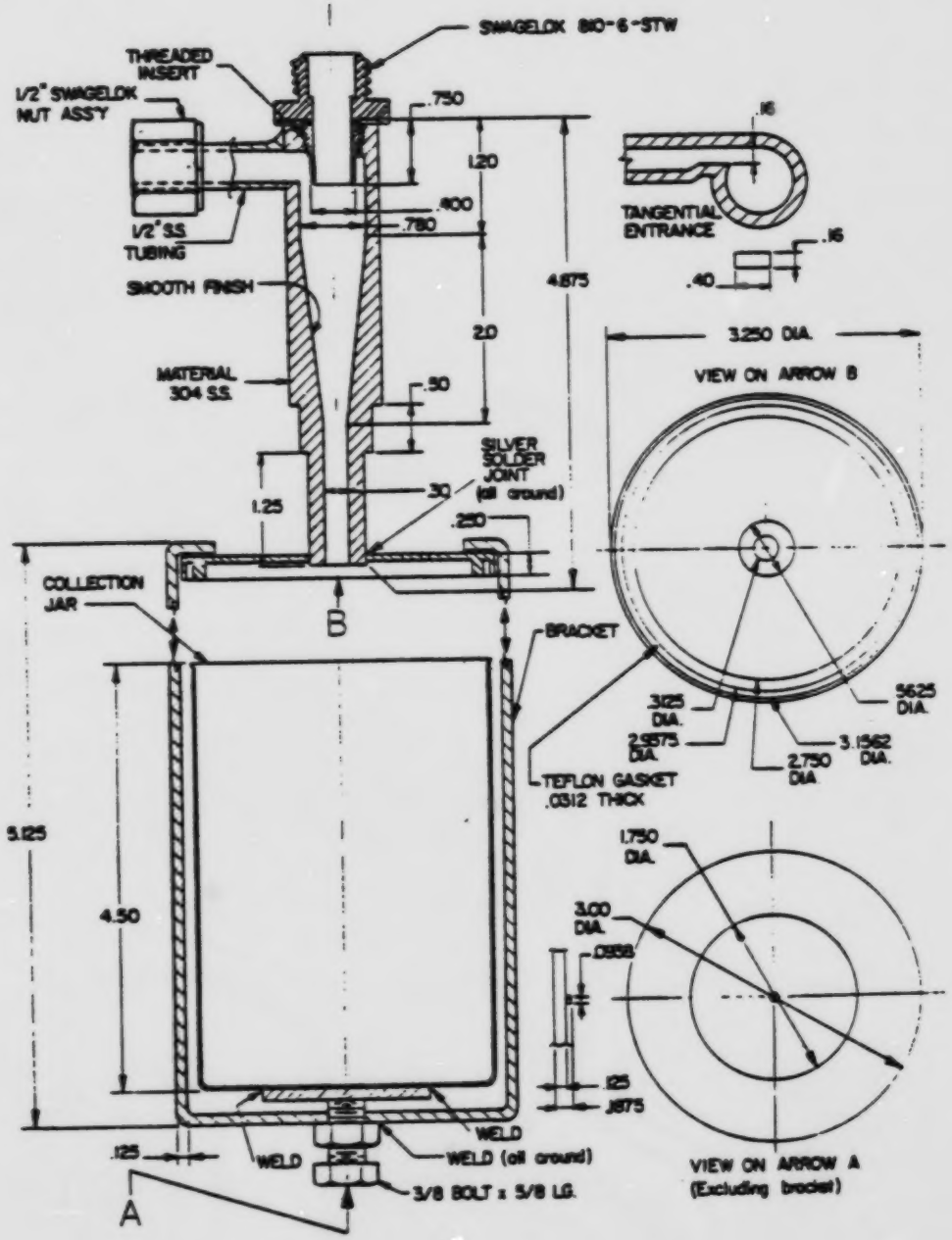


FIGURE 9
CYCLONE



b. Gas conditioning coil - the coil is made from approximately 6 1/2 feet of 1/2 inch O.D. stainless steel tubing. The finished unit has five coils and is approximately 7 inches hign by 5 inches wide. The temperature controller thermistor is placed in a stainless steel tee located at the discharge end of the coil.

c. Filter assembly - the 6 inch O.D. stainless steel Aerotherm filter assembly, shown in Figure 10, consists of a stainless steel filter support, upper and lower filter housings and a quick release clamp. A Viton O-ring seal is located in the lower housing. The filter housings are Teflon coated to facilitate sample recovery. A 5 1/2 inch diameter fibreglass filter is used.

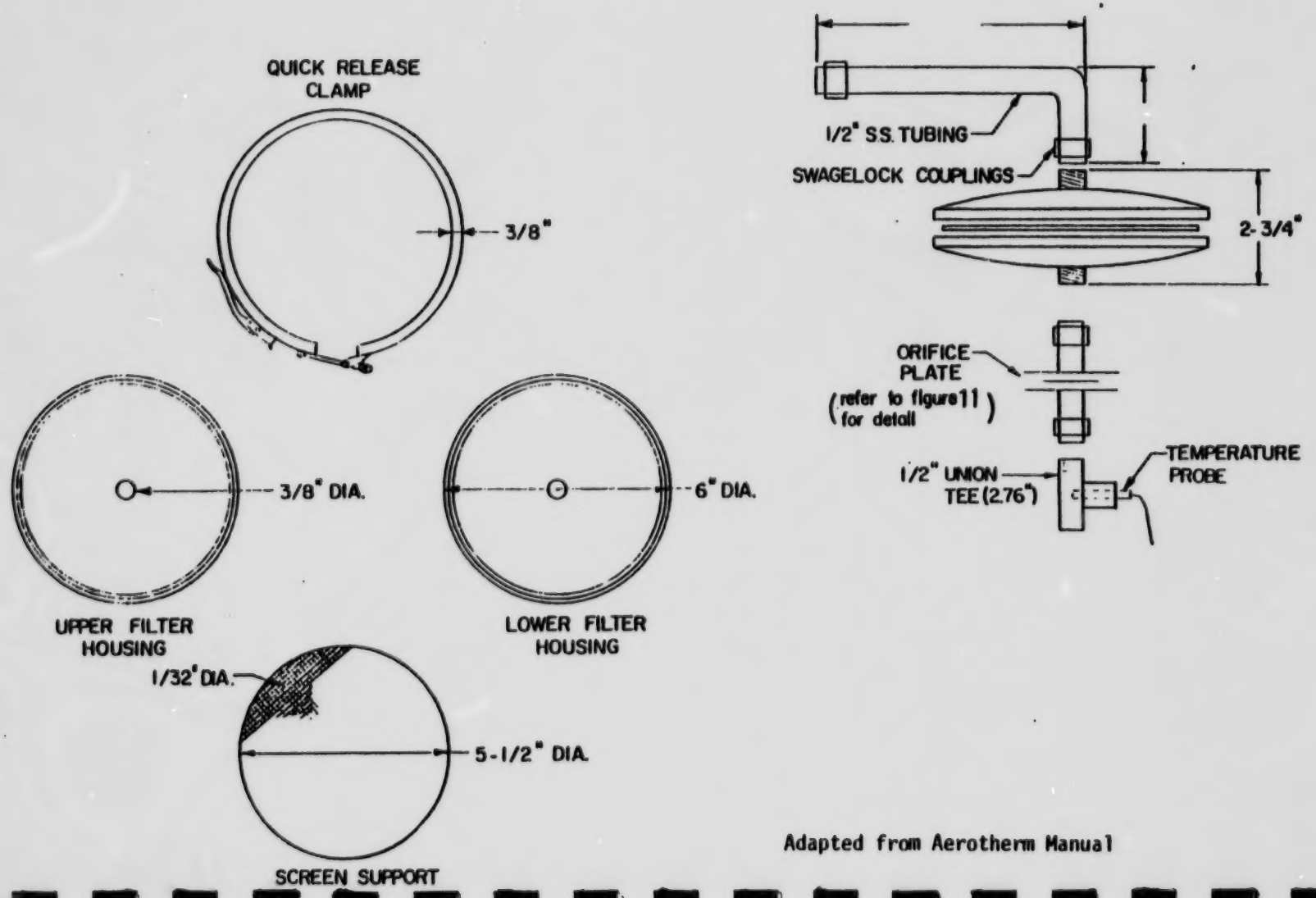
d. Orifice plate assembly - the stainless steel orifice plate assemoly, shown in Figure 11, consists of upper and lower orifice housings, an orifice plate and two Teflon seals. A type K thermocouple is mounted in the lower orifice housing.

4.2.4 Condenser tube

The double pipe neat exchanger/condenser tube, shown in Figure 12, is 15 feet long. The condenser tube is constructed from three sizes of tubing; a 7/16 inch O.D. Teflon tube inside a 13/16 inch O.D. Tygon tube and a 1 1/4 inch O.D. Tygon tube around both of these tubes. A 2 inch diameter plastic hose surrounds the unit to protect it from damage. Ice water is pumped up the inner annulus of the condenser, counter-current to the gas flow and returns down the outer annulus of the assembly.

FIGURE 10

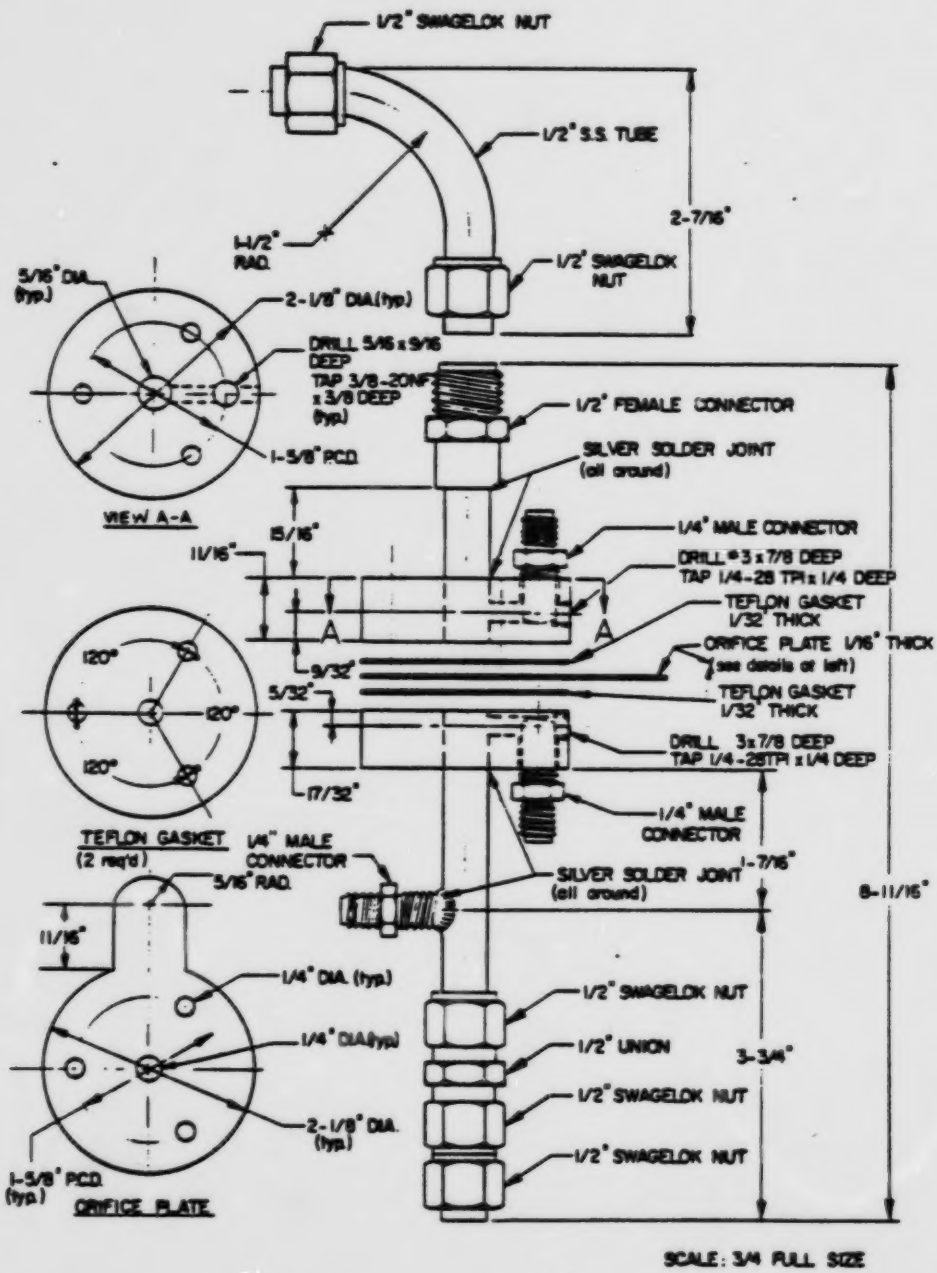
FILTER ASSEMBLY



Adapted from Aerotherm Manual

FIGURE 11

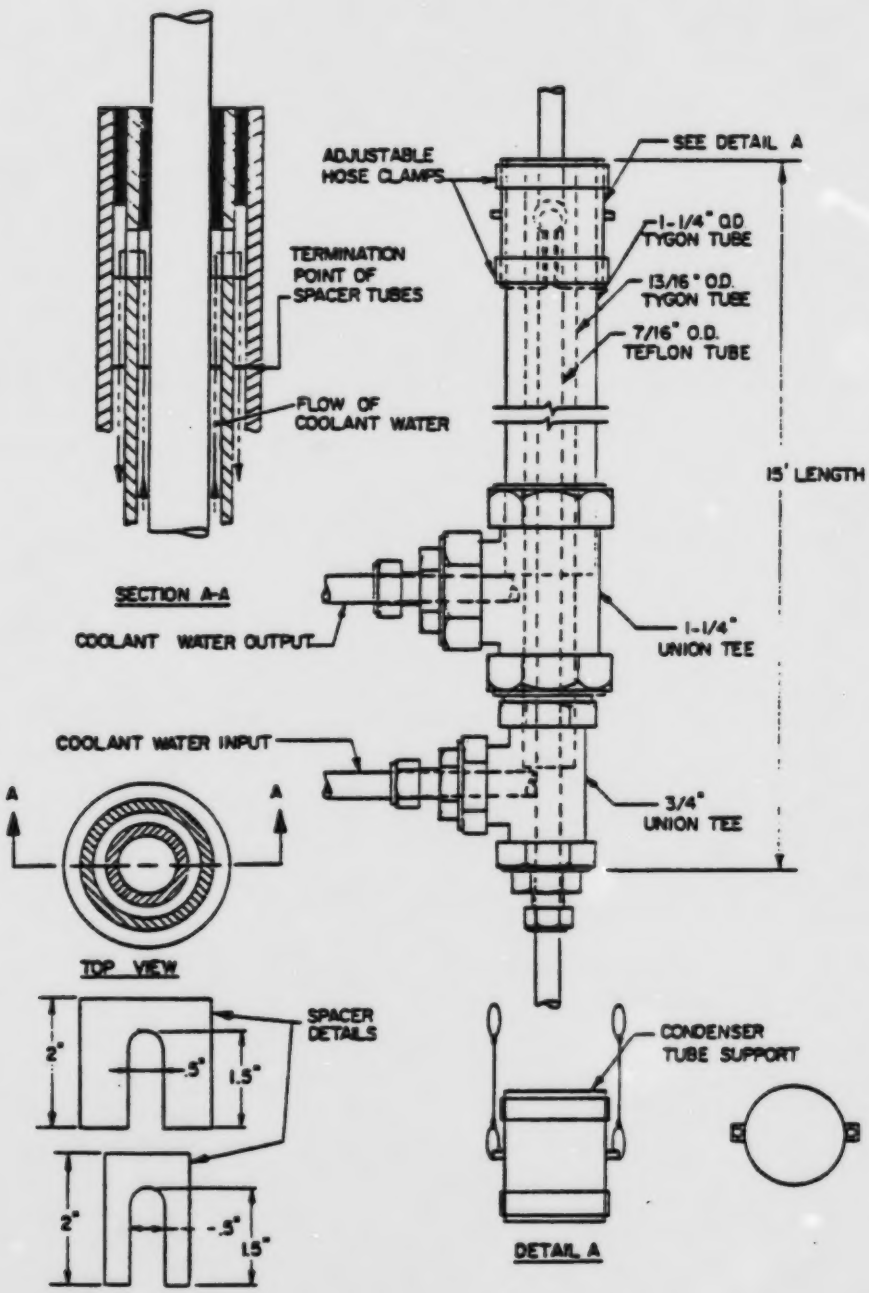
ORIFICE PLATE ASSEMBLY



SCALE: 3/4 FULL SIZE

FIGURE 12

.CONDENSER TUBE



4.2.5 Impinger assembly

The impinger assembly, shown in Figure 13, comprises four stainless steel impingers, a coolant circulating pump and a fibreglass carrying case, which serves as an ice bath during the sampling operation.

The impingers, shown schematically in Figure 14, are 12 inches high and 2 3/4 inches diameter. Connections between the impingers are made with 1/2 inch diameter stainless steel tubing and Swagelok fittings. The impingers are sealed with large diameter Teflon caps and Viton O-rings. A thermocouple mounted in the cap of the fourth impinger monitors the temperature of the gas sample.

The submersible pump, with a maximum capacity of 20 gpm, is used to circulate ice water from the ice chest through the condenser tube.

4.2.6 Vacuum pump

A vane type Gast Model 1022 vacuum pump is shown in Figure 15. An equivalent vacuum pump from another manufacturer is acceptable. The pump has a 3/4 HP motor, a flow rate of 10 cfm at 0 inches Hg and weighs 59 lbs. Self-lubricating carbon vanes produce a smooth, pulse-free gas flow. Coarse and fine control valves allow precise flow settings for isokinetic sampling. Aluminum filter and muffler jars on the pump inlet and outlet provide a quiet operation and a clean air stream to the dry gas meter in the control unit. Quick disconnect fittings allow fast, easy hose connections.

FIGURE 13

COOLANT RECYCLING SYSTEM AND IMPINGER ASSEMBLY

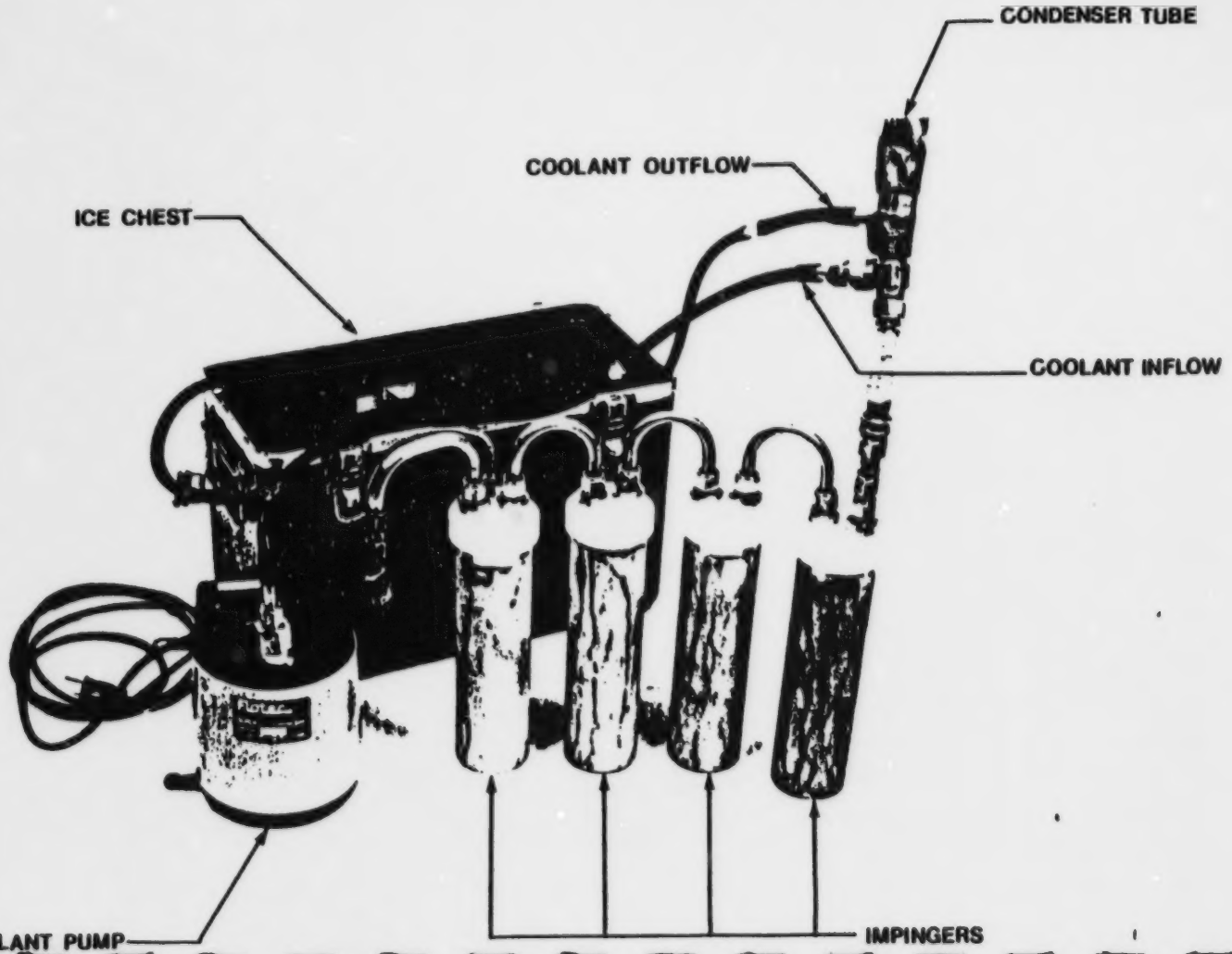


FIGURE 14

IMPINGER TRAIN

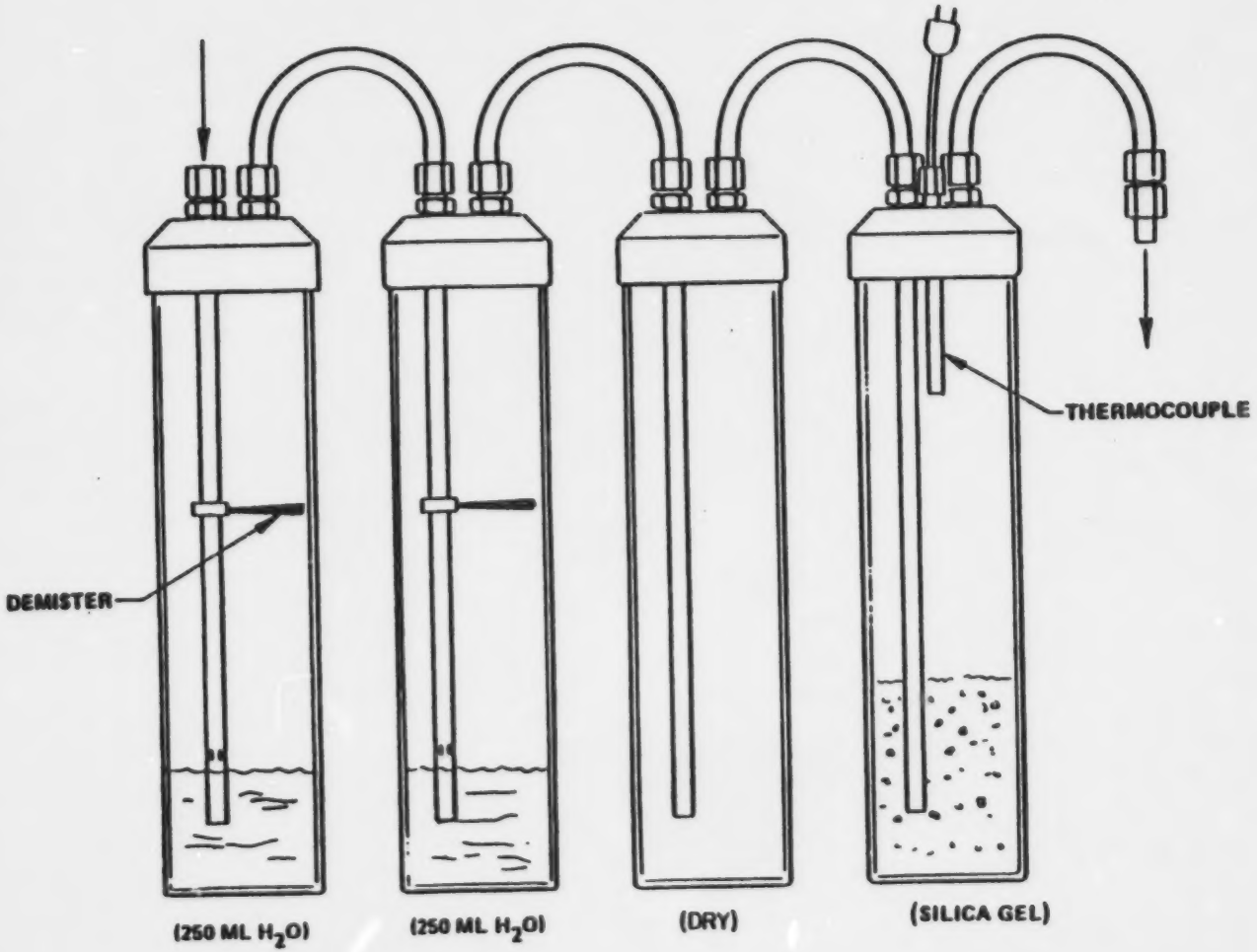
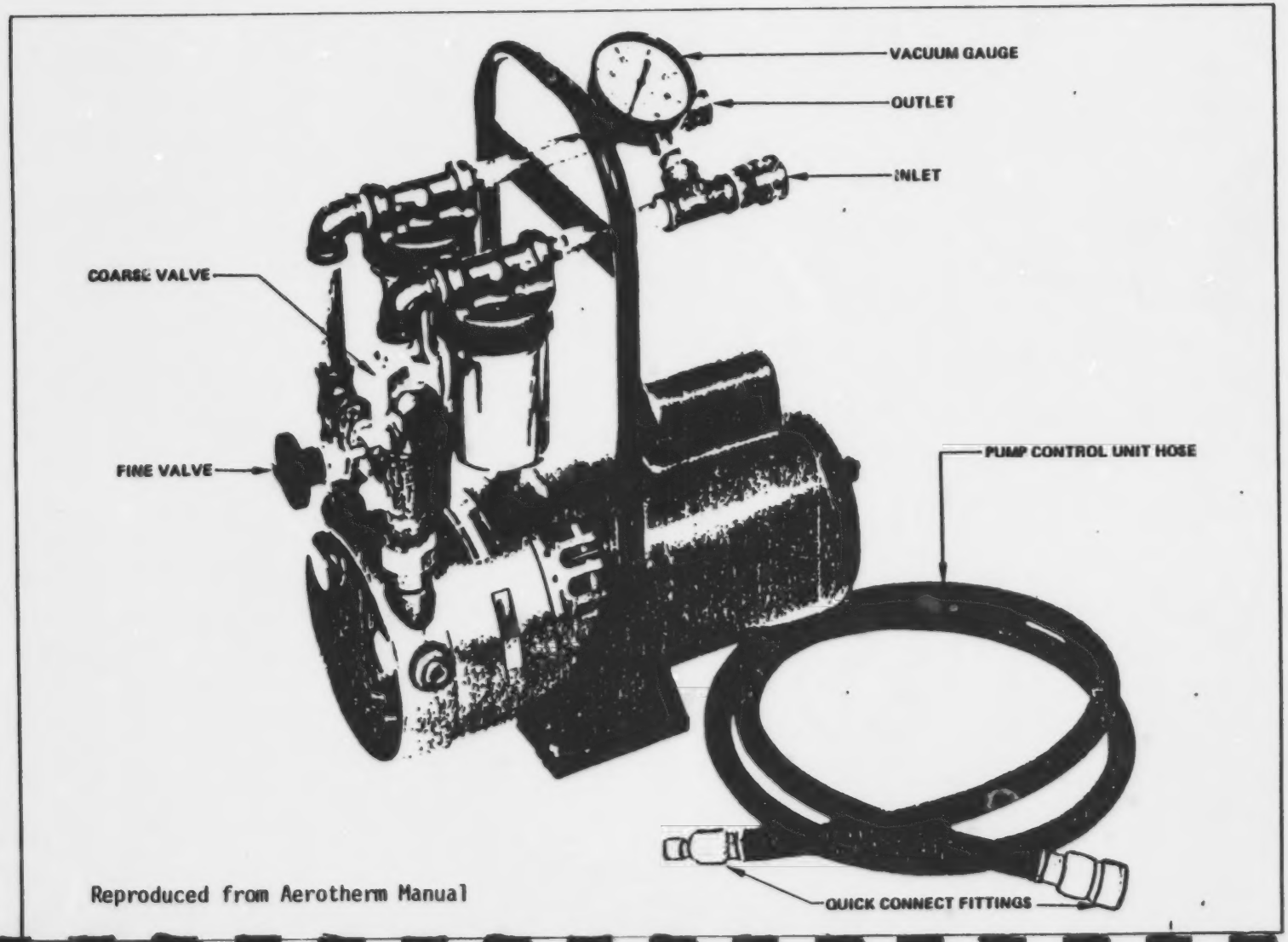


FIGURE 15

VACUUM PUMP



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4.2.7 Control unit

The Aerotherm control unit, shown in Figures 16 and 17, contains the control and measurement instruments and gauges required to conduct an isokinetic stack test and to obtain other pertinent sampling information. Figure 18 shows a schematic of the control unit wiring. The major components of the control unit are:

a. Dry gas meter - used to obtain total sampling volume, to check sampling rates and to check for system air leaks.

b. Temperature controllers and indicator - a digital temperature indicator and an eight-point selector switch are used to monitor temperatures in the stack, probe, cyclone, impingers and dry gas meter inlet and outlet. Adjustable temperature controllers on the control unit are used to set the temperatures of the probe and cyclone heaters.

c. Elapsed time indicator - a clock is used to indicate the duration of the sampling run and the sampling time at each point of the stack traverse.

d. Magnehelic gauges - used to indicate pitot velocity pressures (ΔP) in the stack or duct and orifice differential pressures (ΔH).

FIGURE 16

CONTROL UNIT

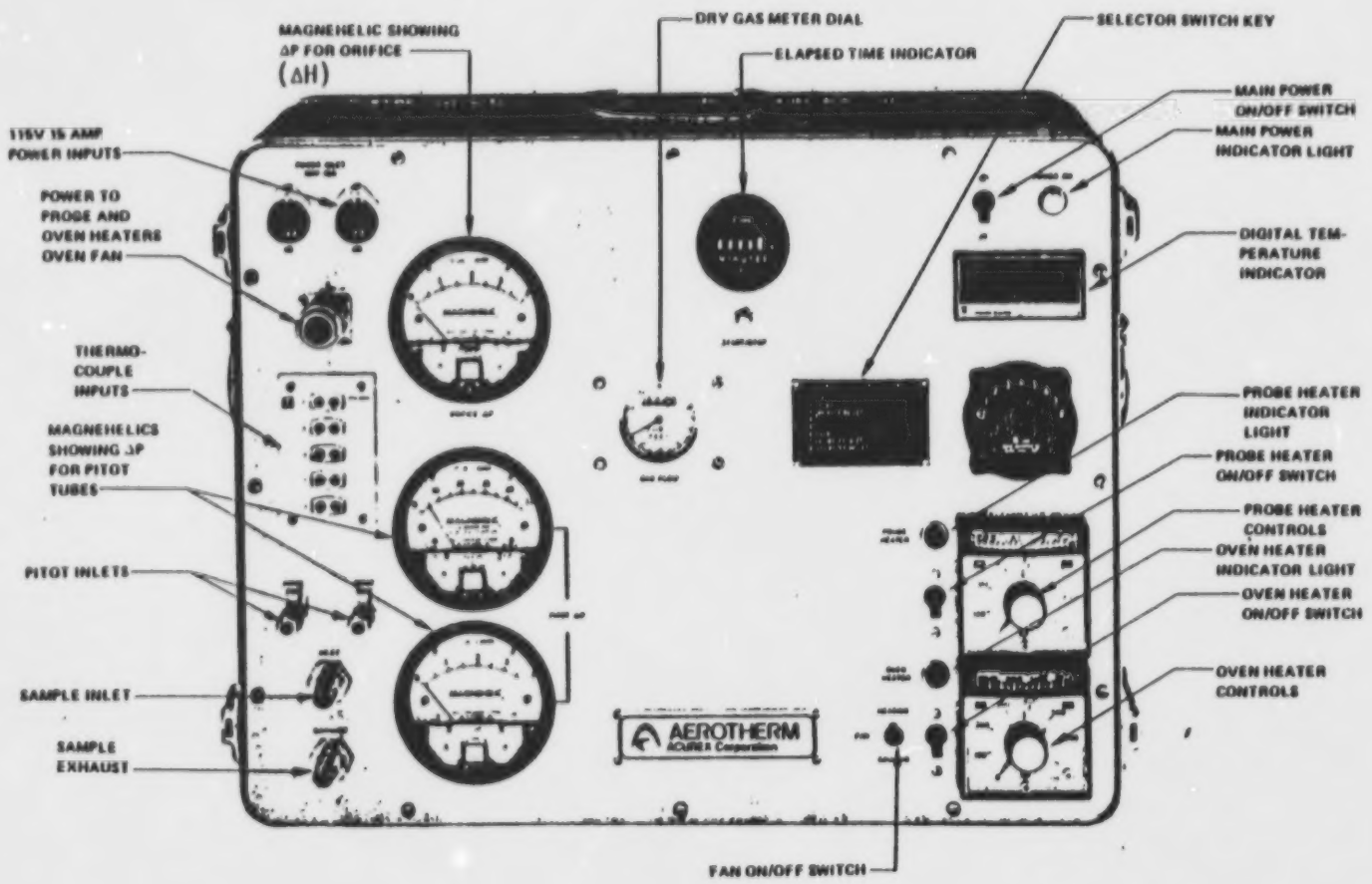

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FIGURE 17

CONTROL UNIT, BACK COVER REMOVED

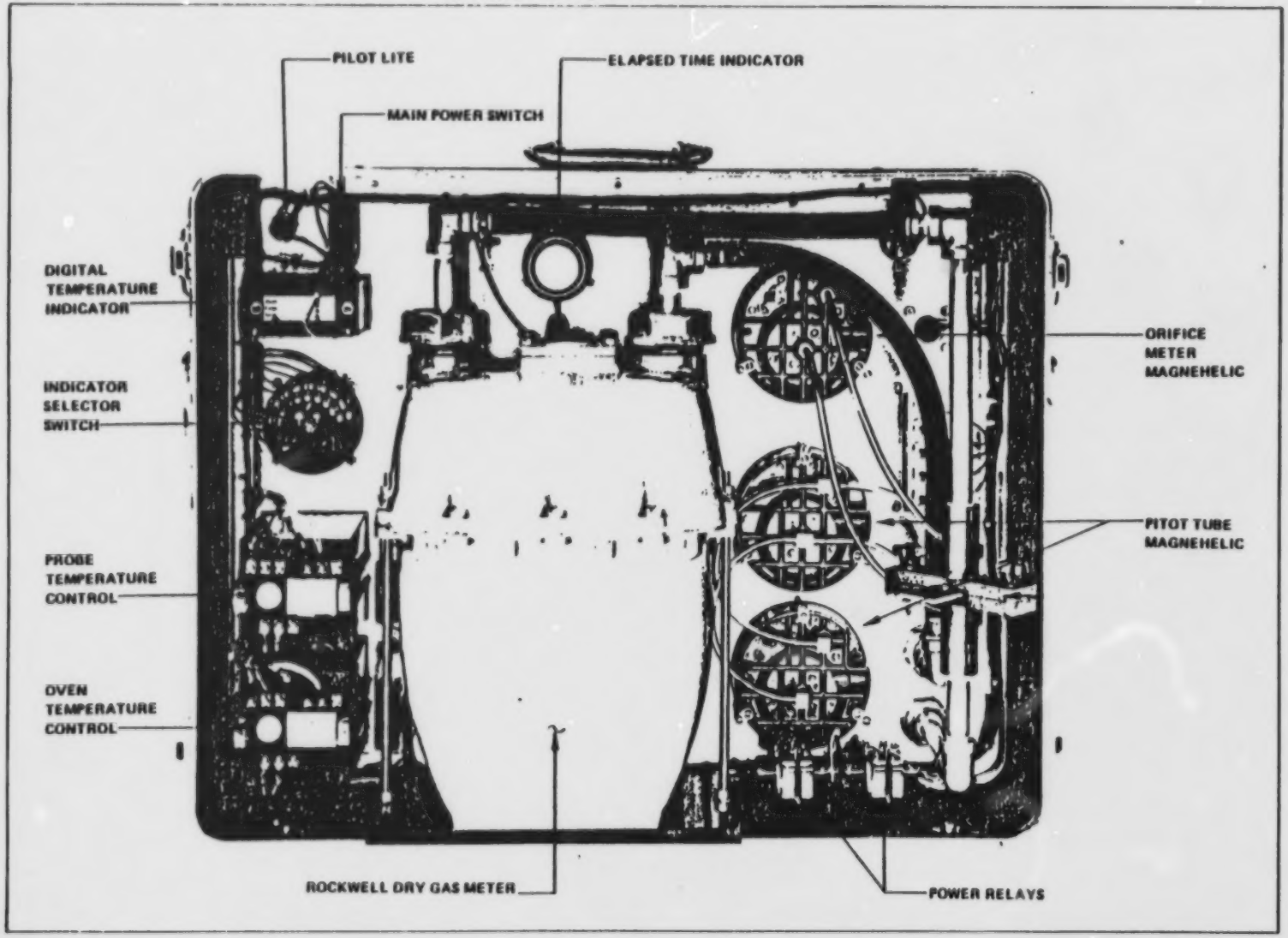

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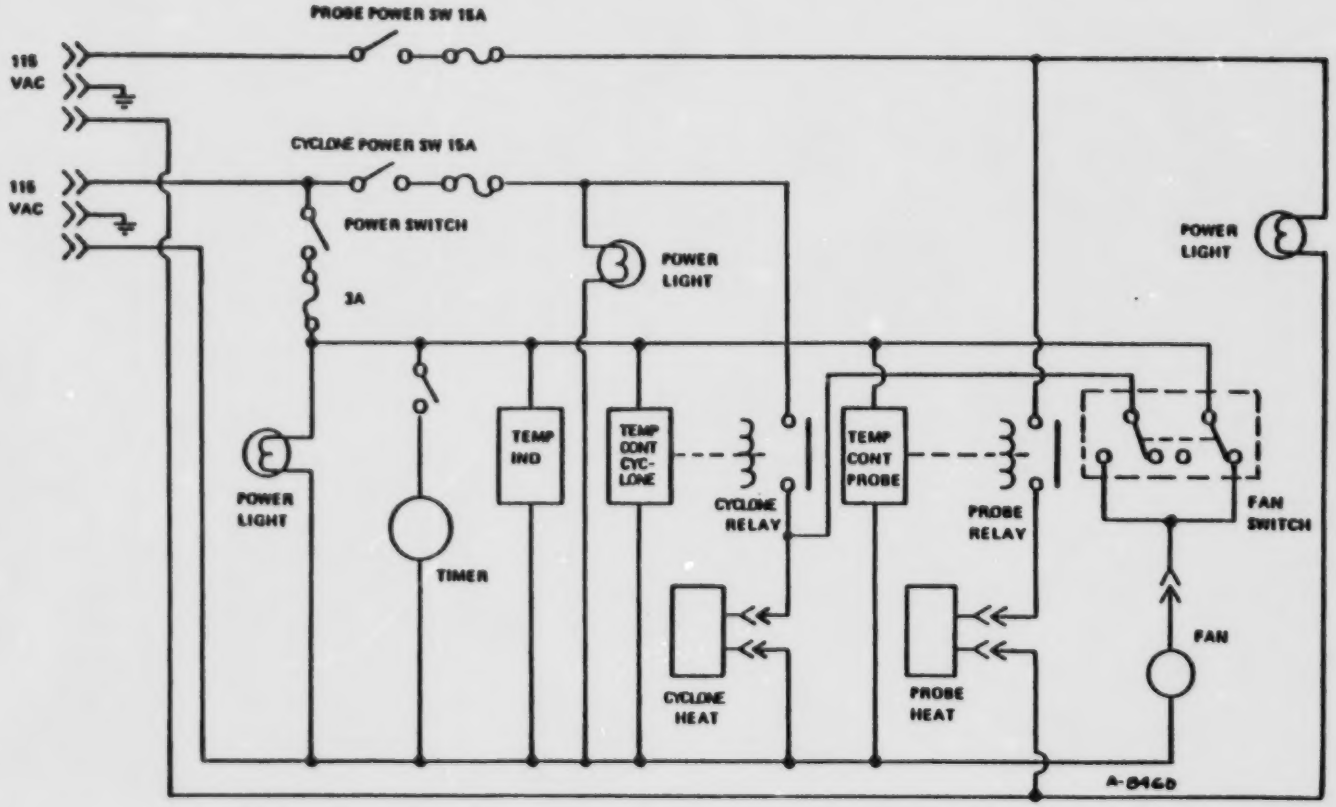
FIGURE 18

CONTROL UNIT, WIRING SCHEMATIC



Adapted from Aerotherm Manual

e. Switches - there are five electrical switches with the following functions:
   i. main power - with pilot light and 3 amp, 115v AC circuit breaker,
   ii. probe heater - with pilot light and 15 amp, 115v AC circuit breaker,
   iii. cyclone heater - with pilot light and 15 amp, 115v AC circuit breaker,
   iv. blower power,
   v. elapsed time start/stop switch.

f. Umbilical line connections - contains multipoint connectors with AC power leads to the sample box, blower and probe; dual pin thermocouple connectors for the stack, probe and impinger thermocouples; pitot tube pressure line connectors and two power connectors.

4.2.8 Umbilical line

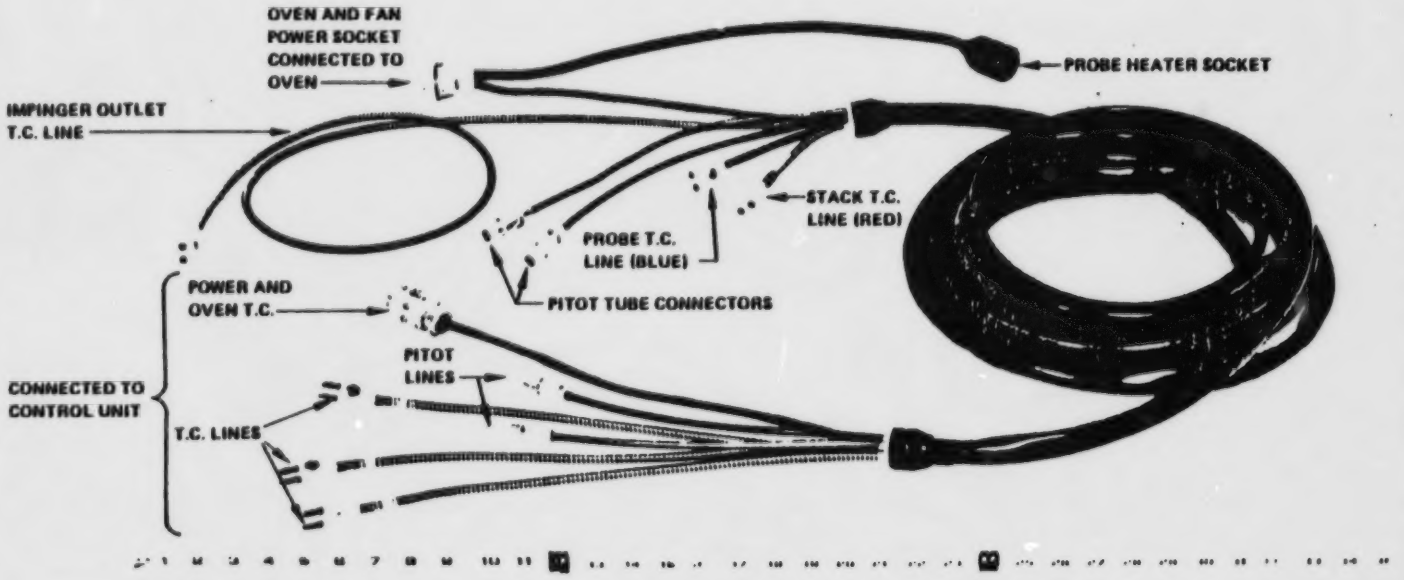
An umbilical line, 25 feet long, connects the probe and sample box to the control unit. The line, shown in Figure 19, consists of a number of power cords, thermocouple and pitot tube connections and features color-coded quick-connectors.

4.2.9 Temperature control system

The sampling train has the capacity for individual temperature control of the probe, cyclone, gas conditioning coil, filter and orifice. The probe is heated by a heating tape and the temperature is controlled using a type K thermocouple located on the sample probe and a Weather Measure model TPC-N temperature controller mounted in the control unit.

FIGURE 19

UMBLICAL LINE



Reproduced from Aerotherm Manual

The cyclone is heated using a single sheath, 800 watt heating element located in the cyclone compartment of the sample box. The temperature is controlled using a type K thermocouple located in tne cyclone compartment and a Weather Measure model TPC-N temperature controller located in the control unit.

The gas conditioning coil is heated using a single sheath, 1600 watt heating element located in the coil compartment. The temperature is controlled using an RFL resistance type thermistor (negative temperature coefficient resistance sensor) located in a tee at the discharge end of the coil and an RFL model 70 proportional temperature controller located on the back of the sample box. The controller is adjusted to give a gas temperature of 200°C. Air from the blower enters the top of the coil compartment and flows over the heater and coil.

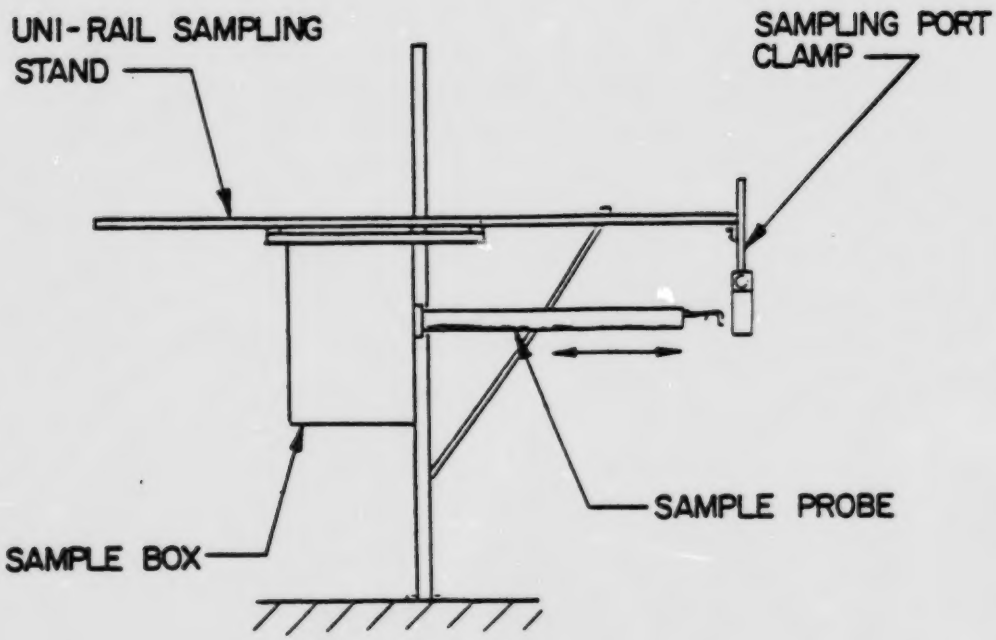
The filter and orifice are heated using a single sheath, 1600 watt heating element located in the filter and orifice compartment. The temperature is controlled using an RFL resistance type thermistor located in the compartment and an RFL Model 70 proportional temperature controller located on the back of the sample box. A type K thermocouple, located in a union welded to the lower half of the orifice plate assembly, monitors the temperature of the gas sample. Tne heater maintains the gas temperature at 200°C through the filter and orifice.

4.2.10 Uni-rail sampling stand

The uni-rail sampling stand consists of a movable roller carriage, a track and an adjustable stand. An adjustable sample port clamp attacnes the uni-rail to the sample port, as illustrated in Figure 20. The sample box is attached to the carriage with removable pins. The uni-rail can be dismantled into two pieces for convenient shipping.

FIGURE 20

UNI-RAIL SAMPLING STAND



4.3 Setup and Operation of Sampler

4.3.1 Test site requirements

A typical test site is illustrated in Figures 21 and 22. The requirements of a test site are:

a. sample ports
b. sampling platform
c. electrical power.

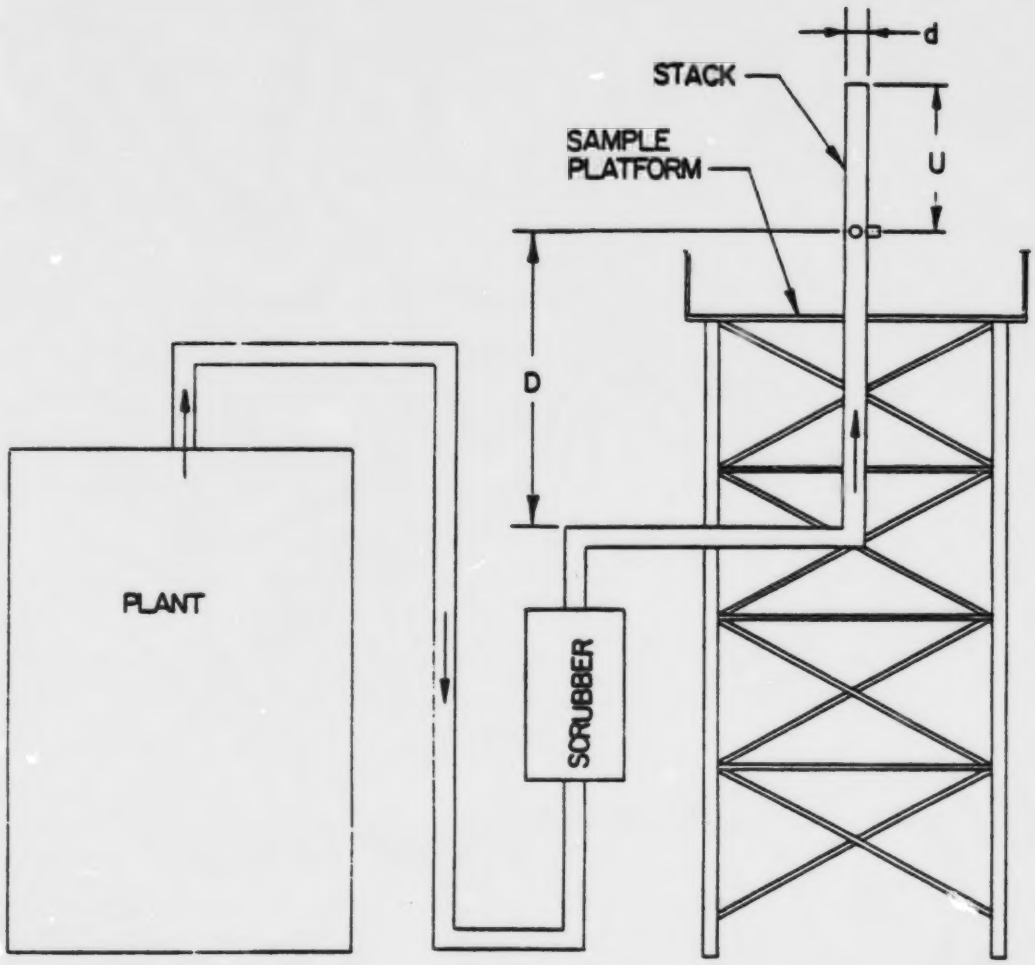
a. Sample Ports

Under ideal conditions, two 3 inch diameter sample ports of 4 inches in length situated 90 degrees apart on the stack or duct are required. Use of a 3 inch gate valve and spool assembly (Figure 7) with a threaded probe cap and seal prevents either the escape of toxic stack gases under positive static pressure conditions or the ingress of air into the stack under negative static pressure conditions.

In accordance with Federal stack testing regulations, the number of sampling points inside the stack or duct is determined by the number of duct diameters upstream and downstream from any restriction or bend in the stack or duct. Under ideal conditions, the ports should be located at least 8 diameters downstream and 2 diameters upstream of any deviations from a laminar gas flow. Under conditions where this placement of sample ports is not possible, use of an "egg-crate" straightening vane is suggested. Use of two ports may not be possible because of space limitations due to the configuration of the gasifier.

FIGURE 21

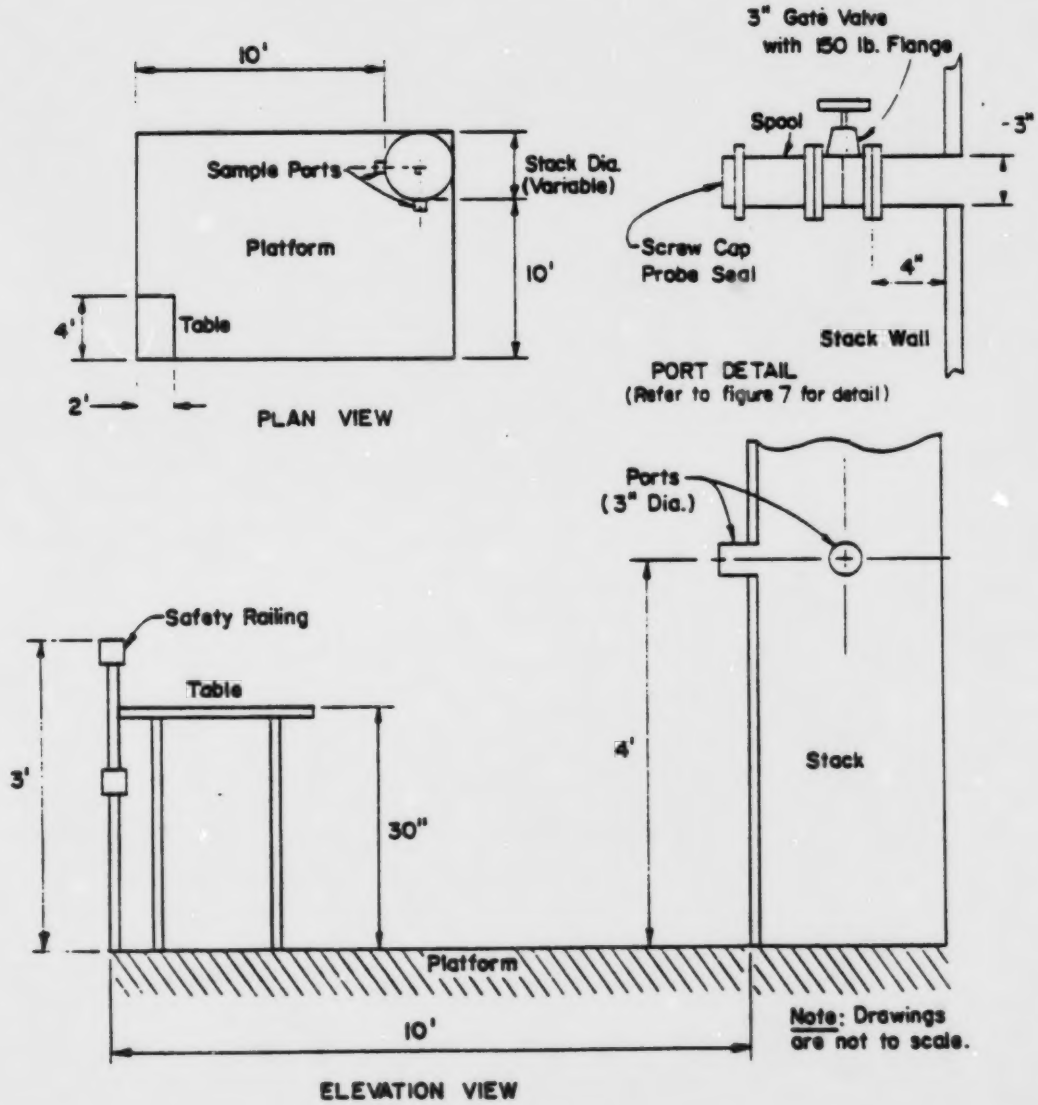
TYPICAL PLANT-STACK CONFIGURATION



U = STACK DIAMETERS UPSTREAM
D = STACK DIAMETERS DOWNSTREAM
d = STACK DIAMETER

FIGURE 22

STACK SAMPLING PLATFORM AND PORTS



b. Sampling Platform

A sampling platform should be suitably placed, of sufficient size to allow safe and convenient testing, and strong enough to support the sampling crew and equipment. All Workers' Compensation Board or equivalent regulations regarding scaffold and raised platform construction must be adhered to.

A portable table of approximately 2 by 4 feet and 30 inches high and a tarpaulin are useful.

c. Electrical Power

Total power requirements of the sampling train are 5 grounded outlets each of 115 volt/60 cycle and 15 amps. Component requirements are: control unit - 30 amps (2 outlets), sample box - 30 amps (2 outlets), vacuum pump and coolant circulating pump - 15 amps (1 outlet with an adapter).

4.3.2 Pretest preparations

a. Preliminary

i. Gasifier Operation

A general knowledge of the operation of the gasifier is useful in determining the characteristics of the discharge gases to be sampled. Information about the temperature and type of gases affects the safety precautions taken during the sampling operation. Static pressure information is useful in determining the care needed in withdrawing a gas sample from the source and the pump vacuum required.

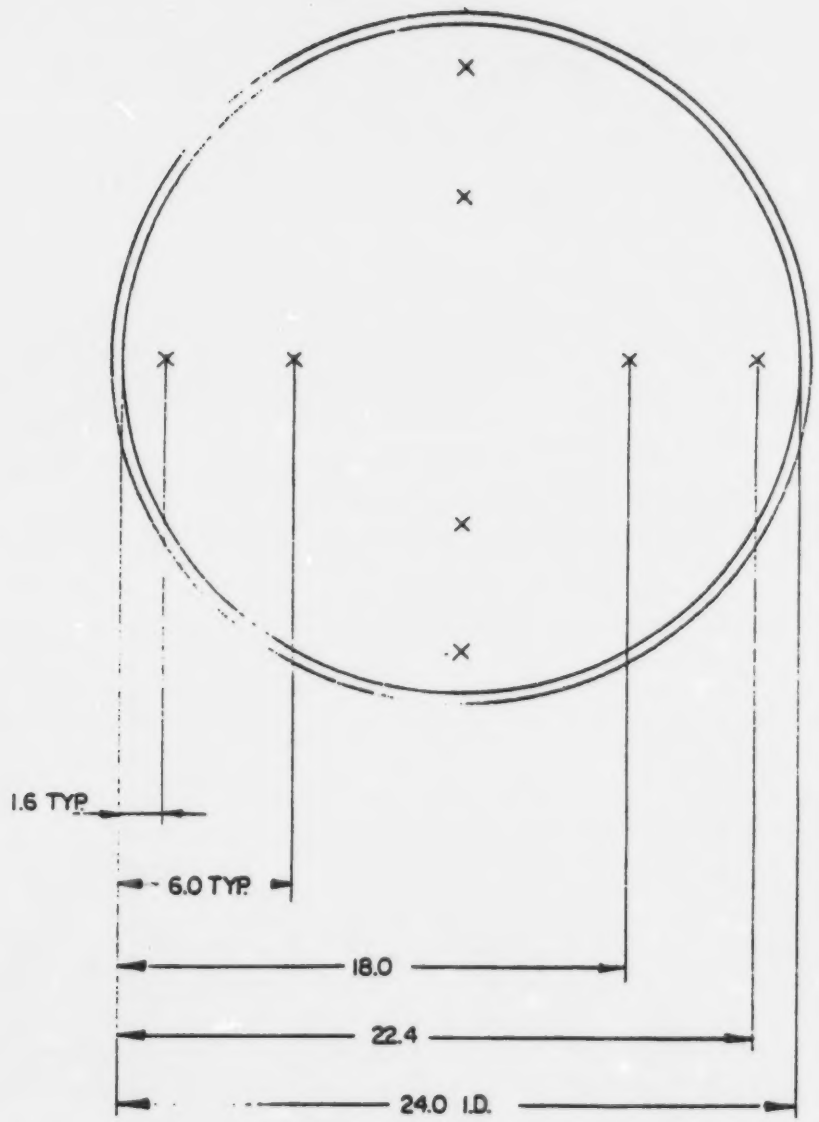
Approximate stack gas temperature, pressure and velocity pressure are required to calculate the nozzle size, orifice plate size and sampling rate for isokinetic sampling. Once the sampling rate has been calculated, the sampling time to collect an appropriate sample volume is determined. Section 7 gives details for calculation of the sampling rate and determination of nozzle size.

ii. Sampling Point Locations

Test parameters, such as the minimum number of points in the sampling traverse, depend on the sampling location in relation to the plant, the stack configuration and the stack inside diameter. Ideally located sampling ports are situated at least 8 stack diameters downstream and 2 diameters upstream of any deviation in laminer stack gas flow. Once these upstream and downstream distances have been estimated, as shown in Figure 21, the number of sampling points can be determined and the distance of these points from the walls of the stack calculated. For example, Table A-1 of EPS Method A, (Appendix A) shows that the minimum number of sampling points under ideal conditions for a 24 inch diameter stack would be 8, with 4 points on each traverse plane. From Table A-2 of Method A, the locations of the four points on each plane are calculated at a distance of 6.7%, 25.0%, 75% and 93.3% from the inside wall of the stack. Therefore, the sampling point locations are 1.6", 6.0", 18.0" and 22.4" from the inside stack wall on each plane, as shown in Figure 23.

FIGURE 23

TRAVERSE POINT LOCATIONS, EXAMPLE*



NOTE: ALL DIMENSIONS ARE IN INCHES.

* UNDER IDEAL PORT LOCATIONS, 24" I.D. STACK

b. Sampling Train Preparation

The sample box and impinger assembly are prepared and assembled in a laboratory or other suitable location close to the test site.

i. The cyclone is weighed to the nearest 0.1 gram, the weight recorded on a stack testing log sheet, and the cyclone connected to the coil in the sample box. An example of a stack testing log sheet is shown in Figure 24.

ii. A 5 1/2 inch diameter glassfibre filter, weighed to the nearest 0.5 mg, is placed in the lower filter housing. The filter unit is assembled, taking care to align the filter and filter support to avoid damage to the filter or an air leak between the filter housings. The filter assembly clamp is adjusted to provide sufficient pressure for a leakproof seal. The filter assembly is connected to the coil.

iii. The orifice plate assembly is connected to the filter assembly. The orifice thermocouple is connected to the orifice plate assembly and the coil thermistor to the coil.

iv. Swagelok caps are placed on the cyclone entrance and the orifice plate assembly discharge ports to prevent contamination during transportation of the sample box to the test site.

FIGURE 24

STACK TESTING LOG SHEET

DATE: _____

PROCESS: _____

PORT LOCATION: _____

OPERATORS: _____

RUN NO.: _____

ORIFICE: _____ "DIA., ΔH @ _____

NOZZLE: _____ "DIA., _____ FT^2 AREA

FILTER WT. AFTER _____ g

BEFORE _____ g

RESIDUE WEIGHT _____ g

BAROMETRIC PRESSURE (P_B) _____ "Hg

STATIC PRESSURE (Ps) _____ "H_2O _____ "Hg

STACK DIAMETER _____ FT, _____ FT^2 AREA

	FINAL WEIGHT	INITIAL WEIGHT	NET WEIGHT
CYCLONE	_____ g	_____ g	_____ g
#1 IMPINGER	_____ g	_____ g	_____ g
#2 IMPINGER	_____ g	_____ g	_____ g
#3 IMPINGER	_____ g	_____ g	_____ g
SILICA GEL IMPINGER	_____ g	_____ g	_____ g

TOTAL IMPINGER GAIN _____ g

LEAK TEST PRE-TEST _____ FT^3

_____ FT^3

_____ FT^3

POST-TEST _____ FT^3

_____ FT^3

_____ FT^3

TEST DATA SECTION

POINT NO.	POINT DIST. "	CLOCK TIME (24 HRS)	STACK GAS TEMP. °F	PROBE TEMP. °F	IMP. OUTL. TEMP. °F	ORIFICE TEMP. °F	CYCLONE TEMP. °F	DRY GAS METER INLET °F	DRY GAS METER OUTLET °F	COIL HEATER ON/OFF	FILTER HEATER ON/OFF	BLOWER ON/OFF	COOLANT PUMP ON/OFF	STACK VELOCITY HEAD ΔP "H_2O	ORIFICE ΔH "H_2O	DRY GAS METER READING FT^3	PUMP VACUUM "Hg
-	-	0	--	--	--	--	--	--	--					----	----		----
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	
12																	
			°F	--				°F	°F	----	----	----	----	----			----
		MINUTES	AVERAGE	--	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	----	----	----	----	----	AVERAGE	TOTAL FT^3	----
		---	°R	--	---	---	---	AVERAGE	°F	----	----	----	----	----	---	---	----
		---	°C	--	---	---	---		°R	----	----	----	----	----	---	---	----

v. The impinger train is prepared by adding 200 ml of distilled water to each of the first two impingers, leaving the third impinger empty and adding approximately 200 grams of silica gel to the fourth impinger. After weighing each impinger to the nearest 0.1 gram and recording the weights on the stack testing log sheet, the impingers are connected and placed, along with the coolant circulating pump, in the impinger carrying case.

vi. Swagelok caps are placed on the entrance to the first impinger and the exit of the fourth impinger to prevent spills and contamination during transportation to the test site.

4.3.3 Equipment installation

The uni-rail is set up on the test platform by attaching the uni-rail clamp to the sample port, and attaching and adjusting the uni-rail leg stand to the required height. The uni-rail should now be in a level position. The sample box is attached to the uni-rail rider with the pins provided and the required power cords are assembled and connected. The control unit and the vacuum pump are placed on the platform and all electrical and hose connections are made. The electrical power switches on the sample box, vacuum pump and control unit are off. All electrical connections should be made to grounded 3-wire outlets.

The umbilical line from the probe and sample box, and the orifice plate pressure lines from the sample box are connected to the control unit. Slide the sample probe into the probe flange on the sample box and connect the probe to the cyclone.

Swagelok connections between the probe, cyclone, coil, filter assembly and orifice plate assembly are tightened. The condenser tube is attached to the orifice plate in the sample box and to tne first impinger. The sample hose from the fourth impinger is connected to the sample pump, then the thermocouple lead is connected from the impinger outlet to the control unit. Sufficient ice and water are added to the ice chest to maintain the temperature of the sample gas in the impingers at less than 10°C. The sampling train is now ready for preheating and the pretest leak check.

4.4 Personal Protective Equipment

Tne high temperatures associated with biomass gasification require that heat-protective gloves and clothing should be worn. When the presence of toxic gases represents a hazard, appropriate respiratory equipment must be worn. Dust respirators should be worn in dusty environments. Normal safety precautions such as the use of hard hats, safety shoes and safety glasses are mandatory.

4.5 Sampling Procedure

After the sampling train has been assembled at the test site, check the sampling train for air leaks by capping the probe entrance and applying 10 incnes Hg vacuum using the vacuum pump. If an air leak greater than 0.02 cfm is present, the leak snould be corrected before starting the sampling run. After completion of the leak check, record the dry gas meter volume on the stack testing log sheet, shown in Figure 24.

The system is preheated by switching on the sample box blower, probe heater, cyclone heater, gas conditioning coil heater and filter heater. The correctly sized nozzle is attached to the probe (Section 7). Allow sufficient time for the probe

heater and sample box heaters to reach their required temperatures (approximately 30 minutes). Start the coolant circulating pump to circulate cool water through the condenser tube.

While waiting for the sampler temperatures to equilibrate, the dry and wet bulb temperatures of the ambient air are taken using a psychrometer.

To place the probe into the stack or duct, carefully slide the probe into the sample port spool until the closed gate valve is encountered, as illustrated in Figure 25. Compress the ceramic fibre seal between the probe and the end flange of the spool by lightly engaging the threaded probe cap into the spool. Fully open the gate valve and slide the probe into the stack to the first sampling point. Seal the probe into the stack by tightening the probe cap securely.

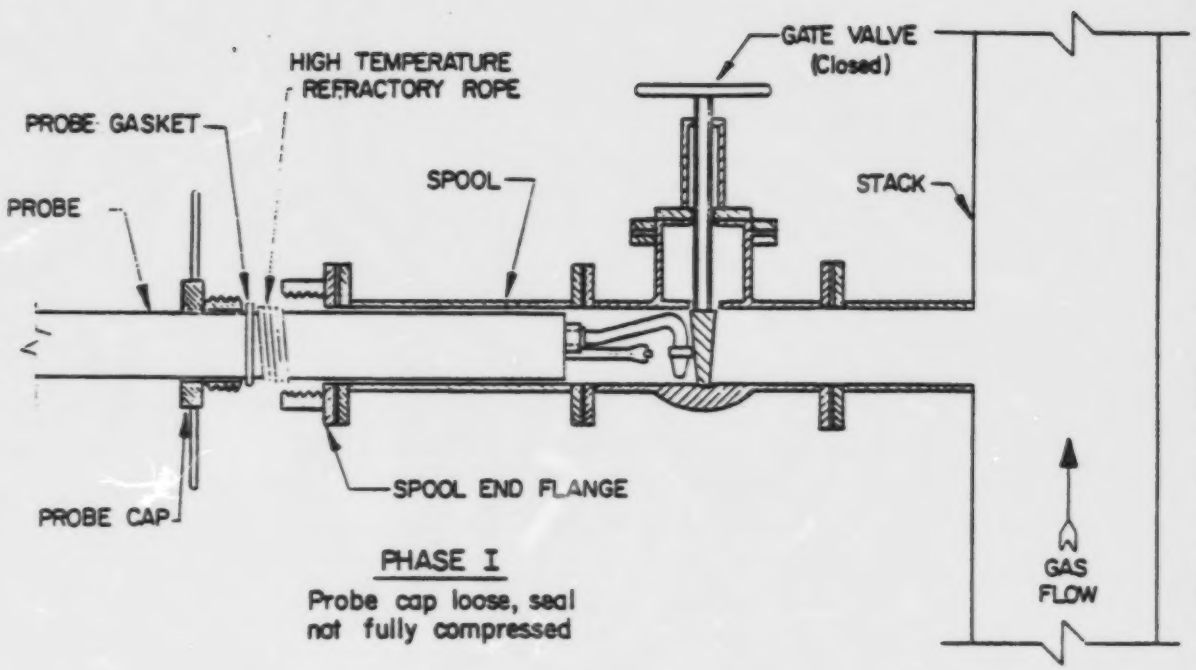
To begin the sampling operation, turn the vacuum pump on, adjust the pump to give the orifice ΔH setting required to attain an isokinetic sampling rate, and start the control unit timer. The orifice ΔH setting is shown on the ΔH Magnenelic gauge on the control unit. ΔH is defined as the differential pressure, in inches of water, of the orifice plate and is a measure of the sampling flow rate in cfm. To calculate and set the correct orifice ΔH setting for each sampling point, the following steps are carried out:

a. Read the velocity head of the probe pitot tube, shown on the ΔP Magnenelic gauge on the control unit.

b. Read the stack temperature (T_s), shown on the stack temperature indicator on the control unit.

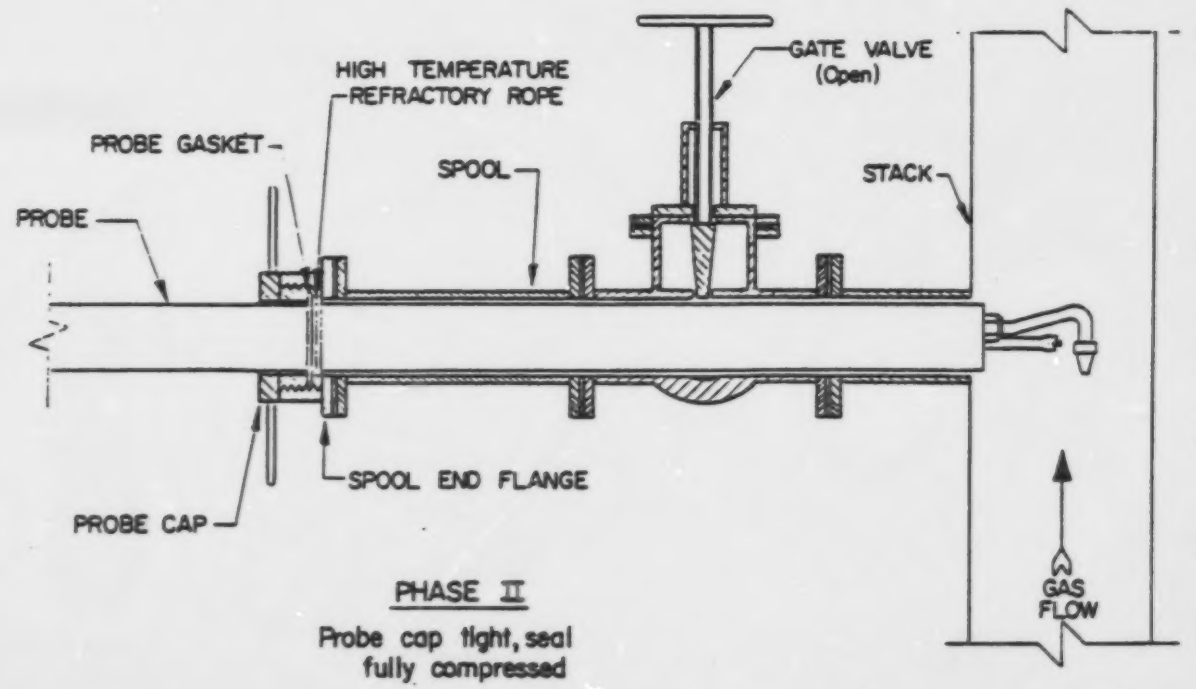
FIGURE 25

PLACING THE PROBE IN THE STACK



PHASE I

Probe cap loose, seal not fully compressed



PHASE II

Probe cap tight, seal fully compressed

c. Insert these values into the standard orifice equation,

$$\Delta H = K \frac{T_o}{T_s} \Delta P$$

As explained in Section 7, K is a constant for a given sampling nozzle diameter and is determined before starting the stack test. T_o is the reference temperature of tne gas in the orifice plate assemoly, 851°R (200°C). Nomographs, programmable calculators or preconstructed isokinetic sampling curves are normally used for fast calculation of ΔH.

d. Adjust tne coarse control valve on the vacuum pump until the ΔH Magnehelic gauge reading is close to the required value, tnen adjust the fine control valve until the exact ΔH reading is achieved. Sampling flowrates should be adjusted within 20 seconds of the probe being placed at a new sampling point.

At predetermined times, loosen the threaded probe cap, slide the probe to the next sampling point and adjust the ΔH setting to coincide with the new pitot tube stack velocity pressure reading. Repeat this step until all points on the stack traverse have been sampled. At intervals, usually 1 to 2 minutes before each move of the probe, record all the required test data on a stack testing log sheet.

After the sampling has been completed, shut off the vacuum pump, stop the control unit timer and record tne final dry gas meter reading on the log sheet. Remove the sample probe from the stack by loosening the probe cap and carefully slide the

probe out of the stack until only the nozzle end of the probe is contained in the spool. Immediately close the gate valve to prevent any gas leakage from the stack and slide the probe out of the spool. Turn off all the heaters in the sampling train, open the sample box door and allow the probe and sample box components to cool for several minutes. Turn off the coolant circulating pump.

If the sampling rate cannot be maintained because the filter has become plugged, the sampling run must be stopped, the filter replaced and the test resumed. The filters and washings are combined for weighing and analysis.

4.6 Sample Recovery

4.6.1 At the test site

After the sampling train components have cooled, remove the sample nozzle from the probe, place it in a protective carrying bag and seal the bag. The end of the probe is sealed with a Swagelok cap.

A mandatory post-test leak check is performed by pulling a vacuum of 5 to 15 inches Hg through the sampling train. The leak rate is recorded on the sampling log sheet. In EPS Method E a leak rate greater than 0.02 cfm is considered excessive and the sample volume is corrected corresponding to a leak rate of 0.02 cfm. However, in gasifier sampling the sample volume is corrected to a leak rate of zero so that the analyzed composition of the gas is correct. A leak of greater than 5 percent of the sample volume is considered excessive. For example, with a sample volume of 30 ft^3, a sampling rate of 1 cfm and a leak rate of greater than 0.05 cfm, the run should be discounted, the leak corrected and the run repeated.

Even though the post-test leak check follows accepted EPS procedures, the rate found during the check is not necessarily representative of the leak rate during the run. Because lower pump vacuums may have been used during the run, a lower leak rate may have occurred in the stack test than that indicated by the post-test leak check.

After the leak check, disconnect the umbilical line from the probe and sample box and disconnect the probe from the cyclone. The probe is disconnected from the sample box, the open end sealed with a Swagelok cap and the probe is placed in a protective carrying case. The condenser tube is disconnected from the orifice plate assembly in the sample box and the tube is drained into the first impinger. The entrance to the cyclone and the orifice plate assembly exit are sealed with Swagelok caps. The orifice lines are disconnected from the orifice, and the sample box is removed from the uni-rail carriage. If more than one run is to be made in a day, the sample box should be left at the test site and only the sample box components removed and taken to the laboratory for weighing and cleaning.

After the condenser tube has been drained into the first impinger, disconnect the condenser tube and first impinger and seal both with Swagelok caps. The lines from the coolant pump to the condenser tube are then disconnected. Carefully wind the condenser tube into a coil so that kinks do not form in the tubing. Disconnect the sample hose and thermocouple plug from the fourth impinger and seal the impinger with a Swagelok cap. Carefully lift the impinger assembly and the coolant pump out of the impinger case, remove the water and ice from the case, then replace the impinger assembly and coolant pump and close the case cover.

The electrical cords, orifice lines and umbilical line are disconnected from the control unit and the control unit cover replaced. The uni-rail stand is dismantled and removed from the sampling platform. Electrical cords and sample hoses are packed in a canvas carrying case.

4.6.2 At the laboratory

The number and type of samples taken in the sample recovery operation is dependent on the information required by the gasifier operator. All the samples must be placed in sealed containers which are clearly identified with a label containing information on the sample source and date of collection. The acetone rinses of each component of the sampling train may be collected separately, or rinses may be combined to give two samples, as described below, a prefilter and a postfilter sample. Acetone is used to rinse the train components because it readily dissolves the tarry residues.

The interior surfaces of the nozzle and probe are rinsed using acetone and a small diameter nylon brush. The rinses are collected in a glass container for the prefilter wash sample.

After removing the Swagelok caps, weigh the cyclone and its contents to the nearest 0.1 gram and record the weight on the log sheet. Transfer the cyclone catch sample to a glass container. After removing the threaded cyclone cap, rinse the cyclone using acetone and a small nylon brush. Add the rinses to the prefilter wash sample.

Using a peristaltic pump and silicon tubing, circulate 3 to 4 rinses, each of approximately 200 ml acetone, through the coil. Collect the rinses and add to the prefilter wash sample.

After carefully dismantling the filter assembly in an upright position, use tweezers to remove tne fibreglass filter and its contents, right side up, and place it in a 6 inch diameter petri disn. Rinse the upper filter housing using acetone and a nylon brush and add this rinse to the prefilter wash sample, which is now complete. Rinse tne lower filter housing using acetone and a nylon brush and add this rinse to the postfilter wasn sample.

Dismantle tne orifice plate assembly by removing the four housing bolts. The upper and lower housings and the orifice plate are rinsed using acetone and a small nylon brusn. Tnese rinses are included in the postfilter wash sample.

Using the peristaltic pump and acetone, rinse the condenser tube 3 to 4 times, using 200 ml of acetone eacn time. The rinses are added to the postfilter wash sample.

Carefully remove the stainless steel impinger loops and Swagelok caps, then remove any exterior surface moisture and dirt from the impingers using paper towels. Weigh the four impingers to the nearest 0.1 gram and record the weights on tne log sheet. Empty the contents of the first three impingers into an acetone-free glass container. Care must be taken to ensure that the condensate sample from the impingers is not contaminated with acetone because acetone may be one of the water soluble organic compounds formed during the gasification process.

Rinse the interior surfaces of the first three impingers witn acetone and add the rinses to the postfilter wash sample, which is now complete.

5.0 ANALYTICAL PROCEDURES

5.1 Introduction

The following sections cover the determination of elemental compositions and calorific values of input and output streams of a gasifier.

Components of the raw producer gas are partially separated in the sampler. Procedures for completing the separation of tar, particulate and condensate fractions are described. During the stack test, tar and particulates are deposited on a number of sampler components. The decision to combine samples for analysis or keep samples separate depends on the information required by the gasifier operator, e.g. particle size distribution can be estimated by determining the weight of the cyclone catch and the filter catch separately. During the sample recovery procedure, described in Section 4.6.2, the acetone rinses containing dissolved tar and particulates are combined into two samples; a prefilter and postfilter sample. This procedure should be reviewed to ensure that all the required information will be obtained.

Procedures described in the following sections utilize conventional laboratory techniques and skills. The use of instrumental methods has been minimized, wherever possible, to allow laboratory personnel to carry out the work in a field laboratory. Determination of the producer gas composition is usually carried out by gas chromatography, and, because of the importance of this analysis, it is recommended that the analyst be completely familiar with the procedure.

Two sources of standard procedures have been used as the basis for the majority of methods: Annual Book of ASTM Standards and Standard Methods for the Examination of Water and Wastewater (ASTM, 1981; APHA, 1980). The latest edition of these reference texts should be consulted.

5.2 Analysis of Feed Materials

This section covers the determination of moisture content, ash, elemental composition and calorific value of biomass feed samples, in particular, wood. Determination of ash content is not required for mass and energy balances. Analyses may be required on one or more feed input streams, which are fed to the gasifier as individual streams or as mixed streams. Procedures for the analysis of additional fuel sources, e.g. lignite, should be accepted standard methods for the material.

5.2.1 Collection of samples

The size and number of feed samples collected should be sufficient to compensate for normal variations in composition of the biomass, incomplete mixing of composite feed streams and variations in moisture content. Place the sample immediately in a vapour tight container or wrapper and allow it to remain in the container or wrapper until it is weighed.

5.2.2 Preparation of samples

The moisture content is determined on the sample as collected. Ash, calorific value and elements are determined on dried samples which have been ground or pulverized to pass a No. 60 (250um) sieve, and which have been well mixed in accordance with a procedure such as quartering, described in ASTM C702-80, Method C.

5.2.3 Procedures

a. Moisture content: Moisture content of the feed sample is determined by oven drying at 103 to 105°C to constant weight, in accordance with ASTM Method D2016-74 or equivalent.

b. Ash: Asn content of tne sample is determined by igniting the sample in a muffle furnace, in accordance with ASTM Method D1102-56, or equivalent.

c. Calorific value: Calorific values of feed samples are determined by calorimetry. ASTM methods D2015-77 and D2382-76 describe suitable procedures. An instrument, such as a Parr Adiabatic Calorimeter, is recommended for the analysis. Pellets of ground samples are prepared before weighing.

d. Elemental composition: Analysis of the feed samples for carbon, hydrogen and nitrogen is carried out using specialized instruments for elemental analysis. Services for elemental analysis are provided by many commercial testing laboratories and the use of their services is recommended. Oxygen can either be measured by these laboratories or can be calculated by difference. For some samples sulfur determination may be required.

5.3 Analysis of Other Input Streams

Chemical analyses will not usually be required on input streams other than feed materials. Data required for other input streams will be obtained during the sampling runs, for example, moisture content of process air.

Water supplied to a scrubber should be analyzed, as a blank, for the same components as the foul water leaving the scrubber.

5.4 Analysis of Producer Gas

This section covers the determination of the chemical composition of clean, dry producer gas containing the following components: hydrogen, oxygen, nitrogen, carbon monoxide, carbon dioxide, methane, ethane and ethylene. Propane and higher hydrocarbons may be determined if required.

Components of a producer gas sample are physically separated by gas chromatography and compared to corresponding components separated under identical operating conditions from a reference standard mixture of known composition.

Many columns have been proposed for gas mixture analyses and any that are capable of the desired separation are acceptable. However, a Porapak Q column and a molecular sieve 13X column in series are commonly used.

5.4.1 Collection and storage of gas samples

During the sampling run, samples are collected from the sampler in plastic film bags, glass sampling tubes or metal bombs. Plastic film bags were found to be the most convenient device in the field and in the laboratory. Sample containers must be checked for leaks before use.

Analysis of gas samples should be completed, if possible, on the day of collection. If sampling bags are used then it is mandatory that hydrogen be analyzed on the day of collection. If necessary, gas samples can be stored overnight at 4°C before completing the analysis.

5.4.2 Procedure

A standard procedure for the analysis of producer gas samples is described in ASTM method D1946-82. Any other procedure which achieves the required separation and sensitivity is acceptable.

A thermal conductivity detector is required for the analysis and a gas sample valve is preferred to syringe injection.

The analysis is best carried out using a gas chromatograph which can accommodate dual columns and allows the carrier gas to be diverted to the detector after passing through each column. Valve switching is one way to achieve this capability. An example of a procedure using valve switching is included as Appendix B.

5.4.3 Calibration

The gas chromatograph should be calibrated using one or more reference standard mixtures of known composition.

One gas mixture can be used if the composition of the producer gas samples will not change from one run to the next. The composition of the standard mixture must be as similar as possible to the expected composition of the samples.

A multi-level calibration using two or more standard mixtures should be used if the composition of the producer gas is expected to change with each run. The concentrations of gases in the standard mixtures should bracket the expected sample concentrations. An assumption that the response of a gas is linear could lead to substantial errors.

5.5 Separation and Analysis of Particulates

This section covers the separation of particulates from the acetone washes of the sampler train components, the treatment of the filter from the sampler, the treatment of a dry cyclone catch from the sampler and procedures for analysis of the dry particulates for elements, ash and calorific value. An outline of the separation scheme is shown in Figure 26.

The particulate samples collected in the sampler may be analyzed separately or may be combined, depending on the requirements of the operator for information about the size of the particulates in the producer gas.

The particulate samples for analysis must be well mixed in accordance with a procedure such as quartering, described in ASTM C702-80, Method C.

Analysis for ash is not required for the mass and energy balances.

5.5.1 Separation and analysis of particulates from acetone washes of sampler components

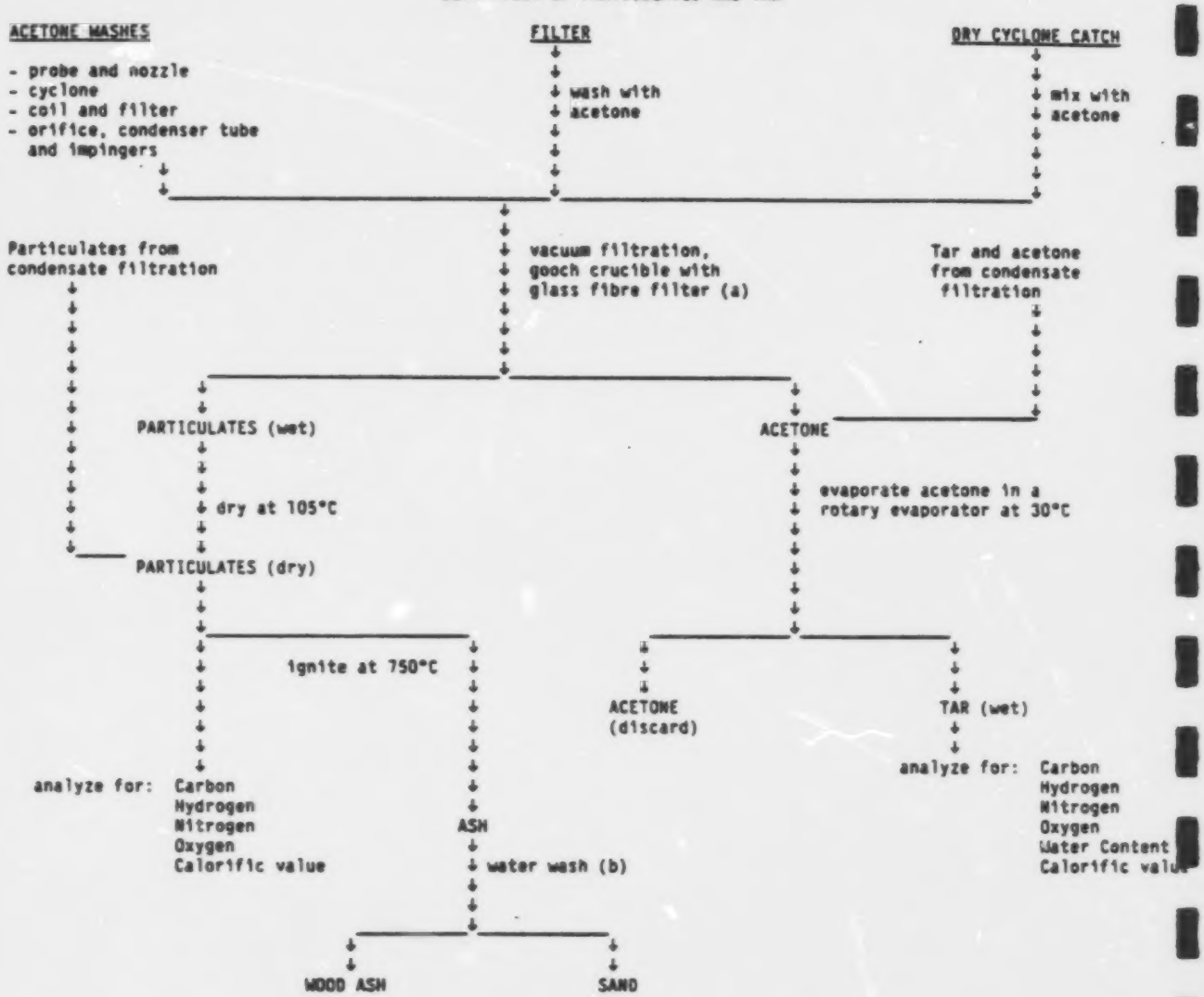
Acetone washes are collected from:

- the probe and nozzle
- cyclone
- coil and filter
- orifice, condenser tube and impingers.

The acetone washes may be processed as individual samples for the entire analysis; filtered individually, weighed and then combined for analysis; or combined prior to filtration.

FIGURE 26

SEPARATION OF PARTICULATES AND TAR



a) samples can be combined or treated separately
b) sand medium fluidized bed gasifier only

Particulates in the condensate sample, if any, are combined with particulates from the impinger wash.

a. Apparatus: APHA method 209, Sections 209A.2 and 209B.2, describes the apparatus required for the separation and drying of the particulates.

b. Materials: Laboratory grade acetone.

c. Procedure: Place the gooch crucible and filter in the filter holder and apply vacuum. Seat the filter paper using about 10 ml of acetone, then immediately filter the sample. Wash the particulates with acetone until the acetone is colourless. Remove the crucible and filter combination from the holder and dry for 1 hour at 103 to 105°C, cool in a desiccator and weigh. Repeat the drying cycle until a constant weight is obtained.

   Retain the acetone filtrate for tar analyses.

d. Analysis: The dry particulate samples are analyzed as follows:

   i. Elemental composition: Analyses of dry particulate samples for carbon, hydrogen, oxygen and nitrogen are best carried out by a commercial laboratory which specializes in these analyses. Oxygen cannot be calculated by difference for particulate samples.

   ii. Calorific Value: Calorific values are determined by calorimetry. ASTM methods D2015-77 and D2382-76 describe suitable procedures. An instrument, such as a Parr Adiabatic Calorimeter, is recommended for the analysis. Pellets may be prepared from the samples or paraffin oil may be added to the loose sample as a combustion aid.

iii. Ash: Ash is determined for the particulate samples by ignition at 750°C for 6 hours in a muffle furnace, as described in ASTM Method D1762-64.

iv. Sand: Particulate samples from a sand medium fluidized bed gasifier will contain sand. After ashing the sample as described above, the ash is washed with water to remove wood ash. The remaining material is dried at 105°C and weighed.

v. Further analyses of particulate samples could include:

- thermogravimetric analysis to determine volatile material and fixed carbon,

- atomic absorption spectroscopy to determine major and minor elements, as described in ASTM Method D3682-78.

5.5.2 Treatment of dry cyclone catch

The dry cyclone catch is mixed with acetone, then it is filtered, washed, dried, weighed and analyzed as described in Section 5.5.1.

5.5.3 Treatment of filter

The glassfibre filter is carefully placed in a large beaker and washed with acetone until the acetone is colourless. The acetone and particulates washed off the filter are then processed as described in Section 5.5.1.

The filter is removed from the beaker, placed on a watch glass, dried for 1 hour at 105°C and weighed. The difference between the weight of the filter after the sampling run and the weight before the run gives the weight of particulates remaining on the filter. To this is added the weight of particulates washed off the filter by acetone, to obtain the total weight of particulates collected on the filter.

Particulates remaining on the filter will be tightly incorporated into the glassfibre matrix. The material washed off the filter during acetone rinsing is analyzed as described in Section 5.5.1 and the results applied to the total weight of particulates collected by the filter.

5.6 Separation and Analysis of Tars

This section covers the separation of dissolved tar from the acetone washes of the sampler train components. Tar samples from the components may be analyzed individually or combined. An outline of the separation scheme is shown in Figure 26. Analyses of tar samples are carried out for elemental compositions, calorific values and water contents.

Tar from the condensate sample is added to tar collected from the impingers, which may be incorporated in a combined postfilter tar sample.

5.6.1 Separation

Acetone solutions of tar are placed in tared round-bottom flasks and the acetone evaporated in a rotary evaporator at 25 to 30°C. The acetone is discarded. The increase in weight of the flask gives the weight of wet tar collected.

5.6.2 Analysis

i. Water content: A Karl Fischer titration is used to determine the tar's water content, in accordance with ASTM method E203-75. No other procedure may be substituted, because the loss of volatile compounds will cause erroneously high results.

ii. Elemental composition: Analyses of the tar for carbon, hydrogen and nitrogen are carried out by a commercial laboratory that specializes in these analyses. Oxygen content may be measured by the same laboratory or may be calculated by difference. Results obtained for the wet tar are corrected to a dry basis.

iii. Calorific value: Procedures for the determination of calorific values are described in ASTM methods D2015-77 and D2382-76. An instrument, such as a Parr Adiabatic Calorimeter, is recommended for the analysis. Paraffin oil is added to the samples as a combustion aid. Results obtained for wet tar samples are corrected to a dry basis.

iv. Further analyses which may be carried out on the tar samples include:

- the determination of ash in accordance with ASTM method D2415-66.

- identification of the major components by gas chromatography, mass spectroscopy and high performance liquid chromatography.

5.7 Separation and Analysis of Condensate

The condensate sample contains water, water soluble organics, water insoluble tar and, possibly, particulates. The separation scheme is shown in Figure 27.

The following procedure is a pressure filtration wnich uses compressed nitrogen to assist the filtration. A vacuum filtration, as described in APHA Method 2090 is acceptable, with modifications similar to those described for tne pressure filtration. These modifications are; the addition of a filter aid to the crucible to separate particulates and tar from tne aqueous phase, and subsequent dissolution of the tar in acetone with the acetone solution collected separately.

5.7.1 Separation of particulates and tar

a. Apparatus

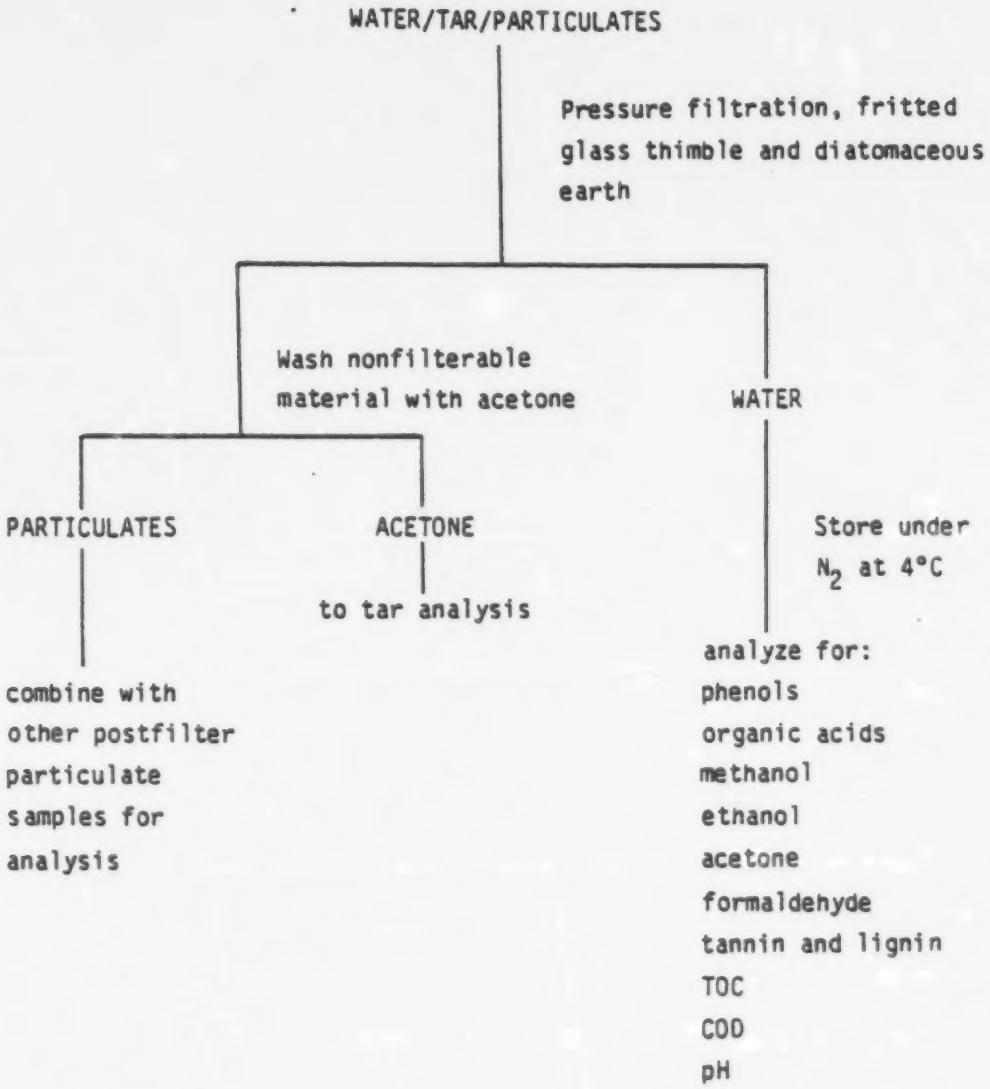
i. medium porosity fritted glass extraction thimble
ii. thimble holder (rubber gooch crucible holder)
iii. suction flask
iv. drying oven, for operation at 103 to 105°C
v. desiccator
vi. analytical balance, 200 g capacity, capable of weighing to 0.1 mg.

b. Materials

i. compressed nitrogen to deliver 15 psig
ii. filter aid such as diatomaceous earth, e.g. Celite 535
iii. laboratory grade acetone

FIGURE 27

SEPARATION OF CONDENSATE COMPONENTS



c. Procedure

i. About 1 g of filter aid is added to the thimble. Dry at 103 to 105°C for 1 hour. Store in a desiccator and weigh immediately before use.

ii. Place the weighed thimble in the holder, add condensate and apply pressure to the top of the tube. A small plastic funnel connected to the nitrogen cylinder by plastic tubing will give an adequate seal over the top of the thimble. Continue adding condensate to the thimble until the entire sample is filtered.

iii. Decant the aqueous filtrate into a container, purge the head space with nitrogen, seal and store at 4°C until required.

iv. Place the thimble and holder on a dry flask. Add acetone to the thimble until the filtrate is colourless, using nitrogen to force the acetone through the filter aid.

v. Rinse the condensate sample bottle with acetone and combine with the acetone wash from the thimble. Evaporate the acetone as described in Section 5.6.1 and analyze the tar as described in Section 5.6.2.

vi. Dry the thimble at 103 to 105°C for 1 hour, cool in a desiccator and weigh. The increase in weight gives the weignt of particulates. The weight of particulates will usually be negligible.

5.7.2 Analysis for water soluble organic compounds

Procedures for analysis of condensate samples are listed in Table 1. Other procedures which achieve the same results are acceptable. For example, ASTM method D3695-78 describes a procedure for volatile alcohols in water by direct aqueous-injection gas chromatography. This procedure can be substituted for the NCASI procedure. Analyses to be carried out are limited only by the time available, the information required by the gasifier operator and the expertise of the analyst.

The analysis for chemical oxygen demand, COD, is not required for mass and energy balances. However, previous work showed that the ratio of COD to TOC was consistent for condensate samples from a gasifier (Aiken, 1983). Once the ratio is established, COD could be used to estimate total carbon in the condensate sample.

The compounds identified in the condensate following the procedures listed in Table 1, will usually account for about 70% of the total carbon (Aiken, 1983). The carbon, hydrogen, oxygen and calorific value contributions of the individual compounds are calculated using accepted values obtained from literature sources (Merck, 1976; CRC, 1982). The ratio of total organic carbon, TOC, to the sum of the individual carbon contributions is calculated. The calculated hydrogen, oxygen and calorific value results are then increased by this ratio. An example of these calculations is shown in Table 2. The error introduced in the mass and energy balances by these manipulations is negligible.

TABLE 1

PROCEDURES FOR ANALYSIS OF CONDENSATE

ANALYSIS	PROCEDURE	DESCRIPTION
pH	APHA No. 423	
organic carbon (total)	APHA No. 505	combustion-infrared method
oxygen demand (chemical)	APHA No. 508A	dichromate reflux method
phenols	APHA No. 510C	distillation and direct photometric method
organic acids	APHA No. 504A	chromatographic separation method for organic acids
tannin and lignin[a]	APHA No. 513	colorimetric
methanol	NCASI Tech. Bull. #310 April 1978[b]	gas chromatographic alcohol analysis
ethanol	"	
acetone	"	
formaldehyde	Appendix D	high performance liquid chromatography

a) determined on residue after distillation of phenols

b) Refer Appendix C.

TABLE 2

EXAMPLE OF CONDENSATE RESULTS AND CALCULATIONS (AIKEN, 1983)

	CONCENTRATION g/L	WEIGHT g	CARBON g	HYDROGEN g	OXYGEN g	CALORIFIC (a) VALUE kJ
Phenols (as phenol)	4.991	0.549	0.420	0.035	0.093	17.83
Organic acids (as acetic)	37.43	4.118	1.647	0.276	2.194	60.00
Methanol	15.31	1.684	0.631	0.212	0.841	38.21
Acetone	3.549	0.390	0.242	0.041	0.108	12.04
Tannin and lignin (as tannic acid)	7.043	0.775	0.404	0.024	0.346	13.01
SUB-TOTAL			3.344	0.588	3.582	141.1
TOC	55.45		6.100			
% Carbon Identified			54.82%			
TOTAL (b) (calculated)			6.10	1.07	6.53	257

a) calorific value for tannic acid measured (formula: $C_{14}H_{10}O_9$), all others from CRC Handbook of Chemistry and Physics.

b) totals for H, O and CV calculated: sub-total x $\frac{100}{54.02}$

Previous work showed that the ratios of carbon to hydrogen, carbon to oxygen and carbon to calorific value remain relatively constant for condensate samples from a gasifier operating at the same conditions (Aiken, 1983). Analysis of a few condensate samples can be carried out and these ratios calculated. Then, total carbon only may be determined for a condensate sample and reliable estimates of hydrogen, oxygen and calorific value may be calculated.

5.8 Analysis of Other Output Streams

This section covers the analysis of other output streams, such as char and foul water from a scrubber.

Solid materials are analyzed as described in Section 5.2

Aqueous samples are analyzed as described in Section 5.7.2

6.0 CALCULATIONS

This Section outlines the computational methodology used to derive an estimate of the energy conversion efficiency. Simple worksheets, included in Appendices E, F and G, are used for the actual computations. An example of the application of this workbook is given in "Testing the Prototype Sampler on a Downdraft Biomass Gasifier" (Aiken, 1983).

6.1 Definition of Symbols

γ - Ratio of reference test meter volume to dry gas meter volume (correlation factor).

ρH_2O - density of water, 0.002201 lb/mL.

A_o - Orifice area, ft^2.

A_s - Cross-sectional area of duct or stack, ft^2.

B_{wo} - Proportion by volume of water vapour in the gas stream, dimensionless.

C_p - S-type pitot tube coefficient.

C_s - Concentration of particulate matter in stack gas on a dry basis at reference conditions, grains/ft^3.

ΔH - Average pressure drop across orifice, in. H_2O.

ΔP - Stack gas velocity pressure, in. H_2O.

D_n - Inside diameter of sampling nozzle, in.

D_o - Orifice diameter, in.

ER - Emission rate of particulate matter from the stack on a dry basis at reference conditions, lb/hr.

I - Ratio of the sampling velocity through the nozzle to stack gas velocity.

K_p - Velocity constant, 85.49 $\frac{ft}{sec}\left[\frac{(lb/lb\text{-}mole)(in.Hg.)}{(^\circ R)(in.\ H_2O)}\right]^{1/2}$

M - Total amount of particulate matter collected, mg.

M_d - Molecular weight of stack gas on dry basis, lb/lb-mole.

MH_2O - Molecular weight of water, 18 lb/lb-mole.

M_s - Molecular weight of stack gas on wet basis, lb/lb-mole.

P_{bar} - Barometric pressure, in. Hg.

P_m - Absolute pressure at dry gas meter, in. Hg.

P_s - Absolute stack gas pressure, in. Hg.

P_{ref} - Absolute pressure at reference conditions, 29.92 in. Hg.

Q_s - Volumetric stack gas flow rate on dry basis at reference conditions, ft^3/hr.

R - Ideal gas constant, 21.83 $in.Hg.ft^3/lb\text{-}mole.°R$.

T - Total sampling time, min.

T_m - Absolute temperature at dry gas meter, °R.

T_{ref} - Absolute temperature at reference conditions, 519°R.

$(T_s)_{avg}$ - Average absolute stack gas temperature, °R.

V_f - Final volume of impinger contents, ml.

V_i - Initial volume of impinger contents, ml.

V_{lc} - Volume of water vapour collected at reference conditions, ml.

V_m - Corrected dry gas volume measured by gas meter, ft^3.

$(V_m)_{ref}$ - Dry gas volume through gas meter at reference conditions, ft^3.

$(V_s)_{avg}$ - Average stack gas velocity, ft/sec.

$(V_w)_{ref}$ - Volume of water vapour in gas sample at reference conditions, ft^3.

0.01543 - Conversion factor, grains/mg.

0.0464 - Constant, ft^3/ml water at 15°C and 1 atm.

13.6 - Conversion factor, in. H_2O/in. Hg.

3600 - Conversion factor, sec/hr.

7000 - Conversion factor, grains/lb.

6.2 Stack Sampling Calculations

Stack gas volume, particulate and gaseous concentration calculations are carried out in accordance with EPS Methods A to F, included as Appendix A. "Fill-in-the-blanks" worksheets for the stack sampling calculations outlined below are presented in Appendix E of this Workbook.

a. Average stack gas velocity, ft/sec (Method B).

$$(V_s)_{avg} = K_p C_p \, (\sqrt{\Delta P})_{avg} \sqrt{\frac{(T_s)_{avg}}{P_s M_s}}$$

b. Volumetric stack gas flow rate on dry basis at reference conditions, ft^3/hr (Method B).

$$Q_s = 3600 \, (V_s)_{avg} \, A_s \, (1-B_{wo}) \left(\frac{T_{ref}}{(T_s)_{avg}}\right)\left(\frac{P_s}{P_{ref}}\right)$$

c. Molecular weight of stack gas on dry basis, lb/lb-mole (Method C).

$$M_d = 0.44(\% \, CO_2) + 0.32(\% \, O_2) + 0.28 \, (\% \, N_2) + 0.28 \, (\%CO) + (\text{other gases})$$

d. Molecular weight of stack gas on wet basis, lb/lb-mole (Method C).

$$M_s = M_d \, (1-B_{wo}) + 18(B_{wo})$$

e. Volume of water vapour collected at reference conditions, ft^3 (Method D).

$$(V_w)ref = 0.0464 \, (V_f - V_i)$$

f. Dry gas volume through dry gas meter at reference conditions, ft^3 (Method D).

$$(V_m)_{ref} = V_m \left(\frac{T_{ref}}{T_m}\right)\left(\frac{P_{bar} + \frac{\Delta H}{13.6}}{P_{ref}}\right)$$

g. Proportion by volume of water vapour in the gas stream (Method D).

$$B_{wo} = \frac{(V_w)_{ref}}{(V_w)_{ref} + (V_m)_{ref}}$$

h. Concentration of particulate matter in stack gas on a dry basis at reference conditions, grains/ft^3 (Method E).

$$C_s = \frac{M\ (0.01543)}{(V_m)_{ref}}$$

i. Emission rate of particulate matter from the stack on a dry basis at reference conditions, lb/hr (Method E).

$$ER = \frac{Q_s\ C_s}{7000}$$

j. Percent isokinecity (Method E).

$$\%I = \frac{(T_s)\ (V_m)_{ref}\ (P_{ref})\ (100)}{(T_{ref})\ (V_s)_{avg}(T)\ (A_n)\ (P_s)\ (60)\ (1-B_{wo})}$$

6.3 Mass Balance Calculations

Sample worksheets giving the procedure for mass balance calculations are included as Appendix F. The worksheets are designed with blank spaces for tne appropriate data to be added.

The final page of Appendix F shows an example of a table which may be used to summarize tne mass balance data.

The following are examples of input and output streams of a typical biomass gasifier. Tnese streams are also illustrated in Figure 1.

IN:

1. Dry Feed
2. Moisture in Feed
3. Dry Air
4. Moisture in Air
5. Others

OUT:

1. Dry Gas
2. Particulates
3. Tars
4. Water Soluble Organics
5. Moisture in Gas
6. Char
7. Moisture in Char (if applicable)
8. Fly Ash
9. Moisture in Fly Ash (if applicable)
10. Others

6.4 Energy Balance Calculations

Sample worksheets for calculating energy balances are included as Appendix G. Blank spaces have been left for the appropriate data to be inserted. The final page of Appendix G is an example of a table for summarizing the results of the calculations.

This section covers an explanation of data required for the energy balance calculations and, where appropriate, shows the procedure for deriving these data.

Typical input and output streams of a biomass gasifier that contribute to the energy balance are listed below.

IN:

1. Heat of Combustion of Dry Feed
2. Process Energy Input (Electro-Mechanical)
3. Entnalpy of Humid Process Air
4. Enthalpy of Moisture in Feed
5. Sensible Heat of Dry Feed
6. Others

OUT:

1. Heat of Combustion of Dry Producer Gas
2. Sensible Heat of Dry Producer Gas
3. Enthalpy of Water in Producer Gas
4. Heat of Combustion of Particulates
5. Heat of Combustion of Tars
6. Heat of Combustion of Water Soluble Organics
7. Sensible Heat of Particulates, Tar and Water Soluble Organics
8. Heat of Combustion of Char
9 Heat of Combustion of Fly Ash

10. Sensible Heat of Char and Fly Ash
11. Heat Loss from Process
12. Others

6.4.1 Heat of combustion

a. Dry gas: The heat of combustion of dry producer gas is calculated as a mass-weighted sum of the standard heats of combustion for the component gases. The gas analysis results can be inserted into a computer program which is included as Appendix H. An example of the program output is included as Appendix I.

b. Feed, particulates, tar, char and fly ash: The calorific values of these materials are measured. The dry basis results are used.

c. Water soluble organics: The calorific value is the sum of the calorific values calculated for each compound measured.

6.4.2 Process energy input

The electro-mechanical process energy includes energy used to operate the gasifier, such as the power consumed by an air compressor.

For example:

E_1 = air blower power

$$= (7.5\text{HP})\left(745.7 \frac{\text{watts}}{\text{HP}}\right)\left(3600 \frac{\text{sec}}{\text{hr}}\right)\left(\frac{8}{100}\right)$$

$$= (7.5\text{HP})\left(745.7 \frac{\text{J/sec}}{\text{HP}}\right)\left(3600 \frac{\text{sec}}{\text{hr}}\right)\left(\frac{8}{100}\right)$$

$$= 1.611 \times 10^6 \frac{\text{J}}{\text{hr}}$$

6.4.3 Enthalpy

a. Water vapour in air feed: The enthalpy value is obtained from standard thermodynamic tables (steam) under "saturated vapour".

b. Moisture in Feed: The enthalpy value is obtained from standard thermodynamic tables (steam) under "saturated liquid".

c. Moisture in Producer Gas: The enthalpy value is obtained from standard thermodynamic tables (steam) under "saturated vapour".

d. H_{ref}: The reference value for enthalpy of moisture in air feed at 15°C is obtained from standard thermodynamic tables (steam) under "saturated liquid" and is 63000 J/kg.

6.4.4 Specific heat

a. Dry feed: The specific heat of most woods varies between 0.45 and 0.65 cal/g°C. For poplar wood 0.5 cal/g°C can be used. Useful conversions:

cal/g°C x 4.185 = J/g°C
Btu/lb = J/kg x 0.00043
J/kg = Btu/lb x 2326

b. Air: The specific heat of air can be found in standard thermodynamic tables (perfect gases), for example: 1.0040 J/g°C at 0°C, 1.0043 J/g°C at 15°C and 1.0061 J/g°C at 100°C.

c. Dry gas: The specific heat of dry gas is calculated in the gas analysis computer program using virial expressions of heat capacities as functions of temperature (Appendix H). An example of the program output is included as Appendix I.

d. Particulates, tar, water soluble organics: Specific heats in the range 1300 to 1700 J/kg-°C can be used for each. For details refer to Perry, Table 3-200, Specific Heats of Miscellaneous Materials (Perry, 1963).

e. Char, fly ash: A specific heat of about 1000 J/kg-°C can be used for char and fly ash. For details refer to Perry, Table 3-200 (Perry, 1963).

6.4.5 Estimation of gasifier system heat losses

Energy loss from the gasifier system can be significant if the vessel and duct walls are not insulated. These energy losses are caused by convective and radiant heat transfer from hot exposed surfaces. An estimate of their value can be made if measurements are obtained for average surface temperatures, surface areas, and local ambient temperature.

The "Chemical Engineers' Handbook" presents simple formulae for estimating these losses (Perry, 1963). For a given surface with an area of "A" square feet and with an average temperature of t_s (°F), the heat loss (Btu/hr) can be estimated as:

$$Q\ (\text{Btu/hr}) = (h_c + h_r)\ A\ \Delta t$$

where h_c = convective heat transfer coefficient
h_r = radiative heat transfer coefficient
t_a = ambient temperature
Δt = ts - ta
Btu/hr = 1.05 kJ/hr

For horizontal ducts:

$$h_c = 0.27\left(\frac{\Delta t}{D_o}\right)^{1/4} \qquad \text{where } D_o = \text{diameter (ft)}$$

For vertical vessels/ducts:

$$h_c = 0.28\left(\frac{\Delta t}{L}\right)^{1/4} \qquad \text{where } L = \text{height (ft)}$$

Radiant heat transfer can be roughly estimated from the following relation:

$$h_r = 0.173\ \epsilon \left[\frac{\left(\frac{Ts}{100}\right)^4 - \left(\frac{Ta}{100}\right)^4}{\Delta t}\right]$$

where ϵ = emissivity, Perry, Table 10-15, (Perry, 1963)

- 0.7 for oxidized iron
- 0.2 for aluminum sheeting
- 0.8 for brick

T_s = average absolute surface temperature, °R (°R = °F + 460)

T_a = average absolute ambient temperature, °R

Both Perry and Caplan provide nomographs for expediting these estimates (Perry, 1963; Caplan, 1976).

For noninsulated systems these losses may be in the order of 10 to 30%. For a well insulated system a loss of 1 to 5% would be typical.

7.0 CALIBRATION OF SAMPLER COMPONENTS

7.1 Isokinetic Sampling

A particulate sampler must be capable of sampling isokinetically. The term means that the sampler nozzle inlet velocity must match the point source velocity during the sampling operation. The velocities are matched by adjusting the sampling rate at the pump according to the relationship

$$\Delta H = K \frac{T_o}{T_s} \Delta P$$

K is a constant for most sampling conditions and is derived from the nozzle and orifice flow equations.

i.e., the nozzle volumetric flow:

$$Q_n = V_n A_n \text{ or } Q_n^2 = \frac{\Delta P}{k_1 \rho_n} A_n^2 \qquad (\Delta P = k_1 \rho_n V_n^2)$$

and the orifice volumetric flow:

$$Q_o = V_o A_o \text{ or } Q_o^2 = \frac{\Delta H}{k_2 \rho_o} A_o^2 \qquad (\Delta H = k_2 \rho_o V_o^2)$$

are combined using the mass conservation relation:

$$\rho_n Q_n = \rho_o Q_o \text{ so } Q_n^2 = \left(\frac{\rho_o}{\rho_n}\right)^2 Q_o^2$$

$$\frac{\Delta P}{k_1 \rho_n} A_n^2 = \frac{\Delta H}{k_2 \rho_o} A_o^2 \left(\frac{\rho_o}{\rho_n}\right)^2$$

$$\Delta H = \frac{\Delta P A_n^2 k_2 \rho_o}{k_1 \rho_n A_o^2} \left(\frac{\rho_n}{\rho_o}\right)^2$$

$$= \frac{k_2}{k_1} \frac{A_n^2}{A_o^2} \frac{\rho_n}{\rho_o} \Delta P$$

$$\text{If } K = \frac{k_2}{k_1} \frac{A_n^2}{A_o^2}$$

and given that $\rho = \frac{\text{a constant}}{T}$, for constant pressure

then $$\frac{\rho_n}{\rho_o} = \frac{T_o}{T_s}$$

therefore $$\Delta H = K \frac{T_o}{T_s} \Delta P$$

where Q_n = volumetric gas flow rate at nozzle, ft^3/min
Q_o = volumetric gas flow rate at orifice, ft^3/min
V_n = velocity of gas at nozzle, ft/sec
V_o = velocity of gas at orifice, ft/sec
A_n = cross-sectional area of nozzle, ft^2
A_o = cross-sectional area of orifice, ft^2
ρ_n = density of gas at nozzle, lb/ft^3
ρ_o = density of gas at orifice, lb/ft^3
ΔP = differential pressure of pitot tube, in. H_2O
ΔH = differential pressure of orifice, in. H_2O
k_1 = equation constant for nozzle
k_2 = equation constant for orifice
T = gas temperature, °R
T_o = orifice temperature, °R
T_s = stack temperature, °R

The control unit contains a set of Magnenelic gauges to measure the pitot velocity pressure, ΔP, and the pressure differential across the orifice, ΔH. The sampler flow rate and, therefore, the nozzle inlet velocity can be varied using the coarse and fine control valves on the vacuum pump.

Determine the size of the nozzle required for isokinetic sampling from an estimate of the stack gas velocity and desired sampling rate (Q_d):

$$D_n = 1.748 \sqrt{\frac{Q_d \, T_s \, P_o}{(V_s)_{avg} \, (T_o)_{avg} \, P_s}}$$

where D_n = diameter of nozzle, inches
Q_d = desired sampling flow rate, $ft^3/min.$
$(V_s)_{avg}$ = average stack gas velocity, ft/sec
P_o = absolute orifice pressure, in. Hg
P_s = absolute stack gas pressure, in. Hg

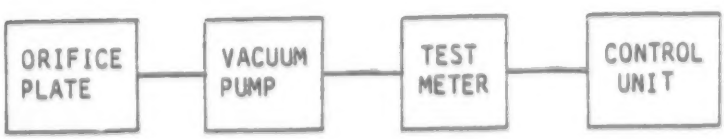
$$1.748 = 12 \sqrt{\frac{4}{60\pi}}$$

7.2 Calibration of the Orifice and Dry Gas Meter

To calculate K factors required in isokinetic calculations, orifice constants (k_o) must be determined by calibrating the orifice plate and dry gas meter with a standard test meter, such as a wet test meter or a bubble meter.

7.2.1 Procedure

Set up the equipment in the following configuration:



Operate the vacuum pump for several minutes to equilibrate the temperature of the system. For each orifice, record initial and final gas meter readings and temperature readings for orifice ΔH readings of 0.50, 0.75, 1.00, 1.25 and 1.50 inches H_2O. Record these readings on an orifice calibration sheet, shown in Figure 28. Using the following equation calculate k_o factors for each orifice setting and average the five k_o factors obtained.

$$k_o = \frac{\Delta H}{\rho_o \, Q_o^{\,2}} \quad \text{from } \Delta H = k_2 \, \rho_o \, V_o^{\,2} \text{ and } k_2 = k_o \, A_o^{\,2}$$

where k_o = orifice constant and Q_o is equivalent to V_d from Figure 28.

The orifice meter should always be operated with pressure differentials of 0.5 in. H_2O or higher to ensure accurate flow measurements.

7.2.2 Dry gas meter correlation factor

The correlation factor (γ) is the ratio of accuracy of the standard test meter to the sampling train dry gas meter. Calculate a γ for each ΔH reading used in the orifice calibration, as shown in Figure 28, and average the five values.

$$\gamma = \frac{V_w \, P_{bar} \, (t_d + 460)}{V_d \, (P_{bar} + \frac{\Delta H}{13.6}) \, (t_w + 460)}$$

FIGURE 28

ORIFICE AND DRY GAS METER
CALIBRATION AND CALCULATION FORM

Date _____ Box No. _____

Barometric pressure, P_{bar} = ____ in. Hg Dry gas meter no. _____

Orifice manometer setting, ΔH, in. H_2O	Gas volume wet test meter V_w, ft^3	Gas volume dry gas meter V_d, ft^3	Temperature				Time θ, min.	γ	$\Delta H_@$
			Wet Test Meter t_w, °F	Dry Gas Meter Inlet t_{di}, °F	Dry Gas Meter Outlet t_{do}, °F	Dry Gas Meter Average t_d, °F			
							Average		

CALCULATIONS

ΔH	$\frac{\Delta H}{13.6}$	γ $\frac{V_w P_b (t_d + 460)}{V_d \left(P_b + \frac{\Delta H}{13.6}\right)(t_w + 460)}$	$\Delta H_@$ $\frac{0.0317\ \Delta H}{P_b (t_d + 460)} \left[\frac{(t_w + 460)\ \theta}{V_w}\right]^2$

γ = Ratio of accuracy of wet test meter to dry test meter. Tolerance = ±0.01

$\Delta H_@$ = Orifice pressure differential that gives 0.75 cfm of air at 70°F and 29.92 inches of mercury, in. H_2O. Tolerance = ±0.15

Reproduced from Aerotherm Manual

where V_w = gas volume of standard test meter, ft^3
V_d = gas volume of dry gas meter, ft^3
t_d = average dry gas meter temperature, °F
t_w = average standard test meter temperature, °F
P_{bar} = barometric pressure, in.Hg.

The correlation factor is used in the calculation of the standard gas volume of a stack test (Appendix E).

$$(V_m)_{ref} = V_m \, Y \, \frac{T_{ref}}{T_m} \left(\frac{P_{bar} + \frac{\Delta H}{13.6}}{P_{ref}} \right)$$

7.2.3 Isokinetic sampling curves

From the previous orifice calibration a series of grapns, each one representing a fixed nozzle diameter, can be constructed. These graphs will allow the operator to instantly determine the correct ΔH (orifice), given the pitot tube ΔP.

$$\Delta H = K \frac{T_o}{T_s} \Delta P$$

$$K = k_o \left(\frac{\pi}{4}\right)^2 D_n^4 \, C_p^2 \left(\frac{1096.2}{144}\right)^2$$

therefore $K = 35.75 \, k_o \, C_p^2 \, D_n^4$

where C_p = coefficient of pitot tube (Section 7.4).

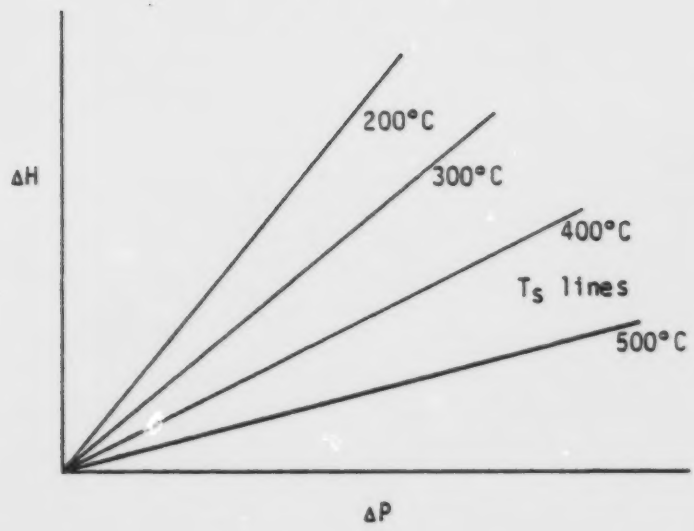
In this equation, substitute the value for C_p and for the nozzle diameter (D_n) to obtain the K factor which is required in the ΔH equation.

Construct sampling curves for several stack temperature settings by substituting a standard orifice temperature of 200°C (T_o = 851°R), the stack temperatures (T_s), and various values for ΔP, to obtain the corresponding value for ΔH.

Figure 29 is an illustration of the curves obtained.

FIGURE 29

ISOKINETIC SAMPLING CURVES



7.3 Use of a Nomograph

A slide rule nomograph, as illustrated in Figure 30, can be used, in place of constructed isokinetic sampling curves or on-site calculations, to determine ΔH settings required in a stack test. Most nomographs make use of a ΔH @ calibration factor for each orifice that must be utilized to accomplish the determination. The ΔH @ of an orifice is the orifice pressure differential in inches of H_2O that yields a volume flow of 0.75 ft^3/min at 70°F and 29.92 in Hg. As shown in Figure 28, ΔH @ factors are calculated using the orifice and dry gas meter calibration values.

$$\Delta H @ = \frac{0.0317\ \Delta H}{P_{bar}\ (t_d + 460)} \left[\frac{(t_w + 460)T}{V_w}\right]^2$$

An average ΔH @ factor is determined from the five values obtained. The allowed tolerance is $\pm$ 0.15. If the average ΔH @ is exceeded by 0.15, the linkages at the top of the dry gas meter should be adjusted until the tolerance level of $\pm$ 0.15 is met.

7.4 Calibration of Pitot Tube

Using a wind tunnel, an inclined manometer and a standard pitot tube with a known coefficient, calibrate the S-type pitot tube as described in Method F of EPS 1-AP-74-1, which is included in Appendix A. Record calibration readings on a pitot calibration sheet shown in Figure 31.

$$C_{p\ S\text{-}type} = C_{p\ std} \left(\frac{\Delta P_{std}}{\Delta P_{S\text{-}type}}\right)^{1/2}$$

FIGURE 30

ISOKINETIC FLOW RATE CALCULATOR

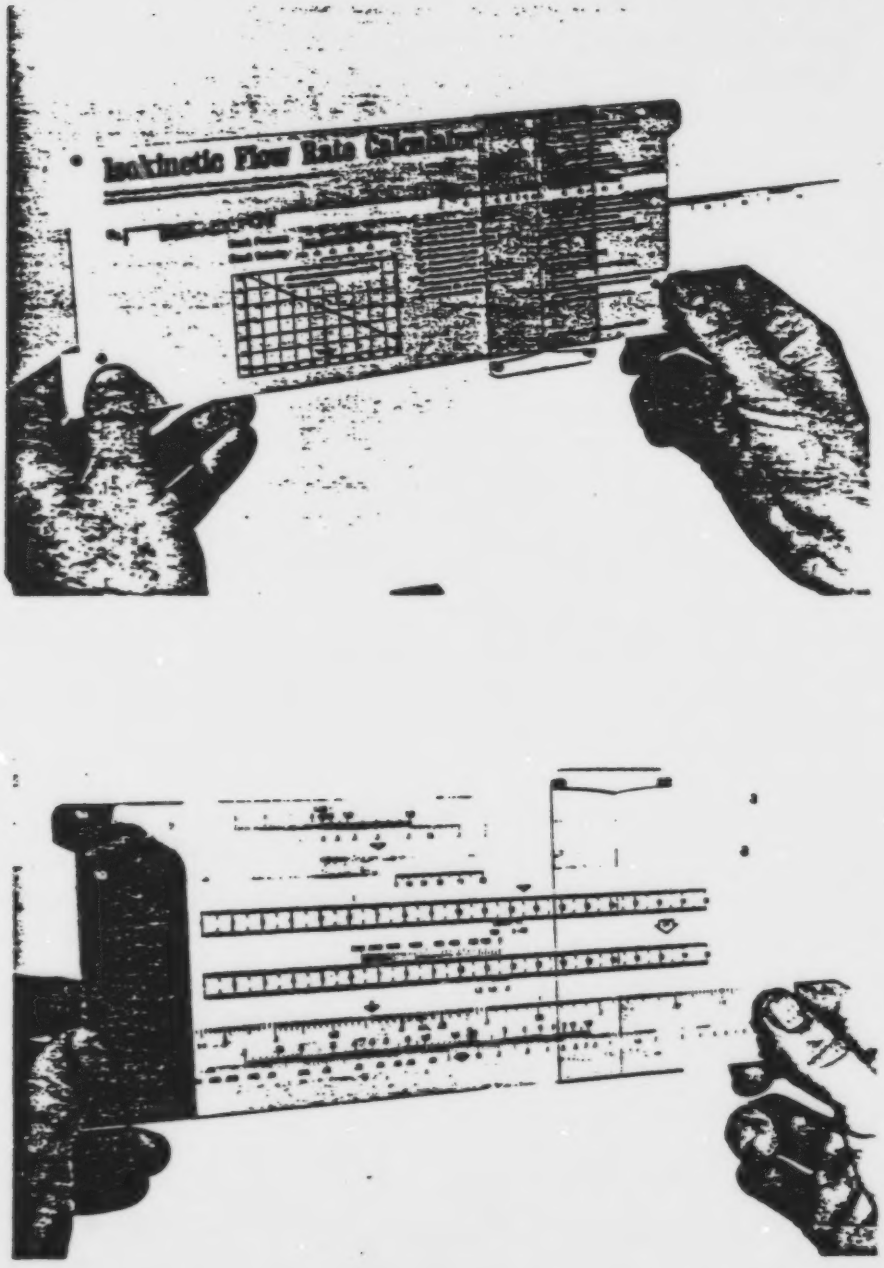


FIGURE 31
PITOT TUBE CALIBRATION FORM

Pitot Identification: _____

Company: _____

Serial Number: _____

Date: _____

Calibrated by: _____

	Side A Calibration			
Run No.	Δp Std.	Δp S-Type	Cp S-Type	Deviation Cp (s) - Cp (A)
1				
2				
3				
		Cp Side A		

	Side B Calibration			
Run No.	Δp Std.	Δp S-Type	Cp S-Type	Deviation Cp (s) - Cp (B)
1				
2				
3				
		Cp Side B		

Where $C_{p\ S\text{-}type}$ = coefficient of S-type pitot tube
$C_{p\ std}$ = coefficient of standard pitot tube = 0.99
ΔP_{std} = velocity pressure measured by standard pitot tube, in. H_2O
$\Delta P_{S\text{-}type}$ = velocity pressure measured by S-type pitot tube, in. H_2O.

7.5 Calibration of Magnehelic Gauges

Using a wind tunnel, an inclined manometer and a standard pitot tube, calibrate each Magnehelic gauge by comparing the velocity readings of the gauge to the inclined manometer readings. Three readings should be taken which cover the range of the gauge. Connect the Magnehelic gauge and the inclined manometer together using a union tee as shown in Figure 32. After connecting the pitot tube pressure lines to the union tee, record the three velocity pressure readings of the inclined manometer and the Magnehelic gauge on a calibration sheet as shown in Figure 33. Calculate a percentage error for each velocity range as follows:

$$\%E_{avg} = \frac{(\Delta P_{std} - \Delta P_{mag})}{\Delta P_{std}} \ 100$$

where $\%E_{avg}$ = percentage error
ΔP_{std} = velocity pressure measured by standard pitot tube, in. H_2O
ΔP_{mag} = velocity pressure of Magnehelic gauge.

A Magnehelic gauge with an average percentage error in excess of 5% must be discarded or repaired.

FIGURE 32

MAGNEHELIC GAUGE CALIBRATION

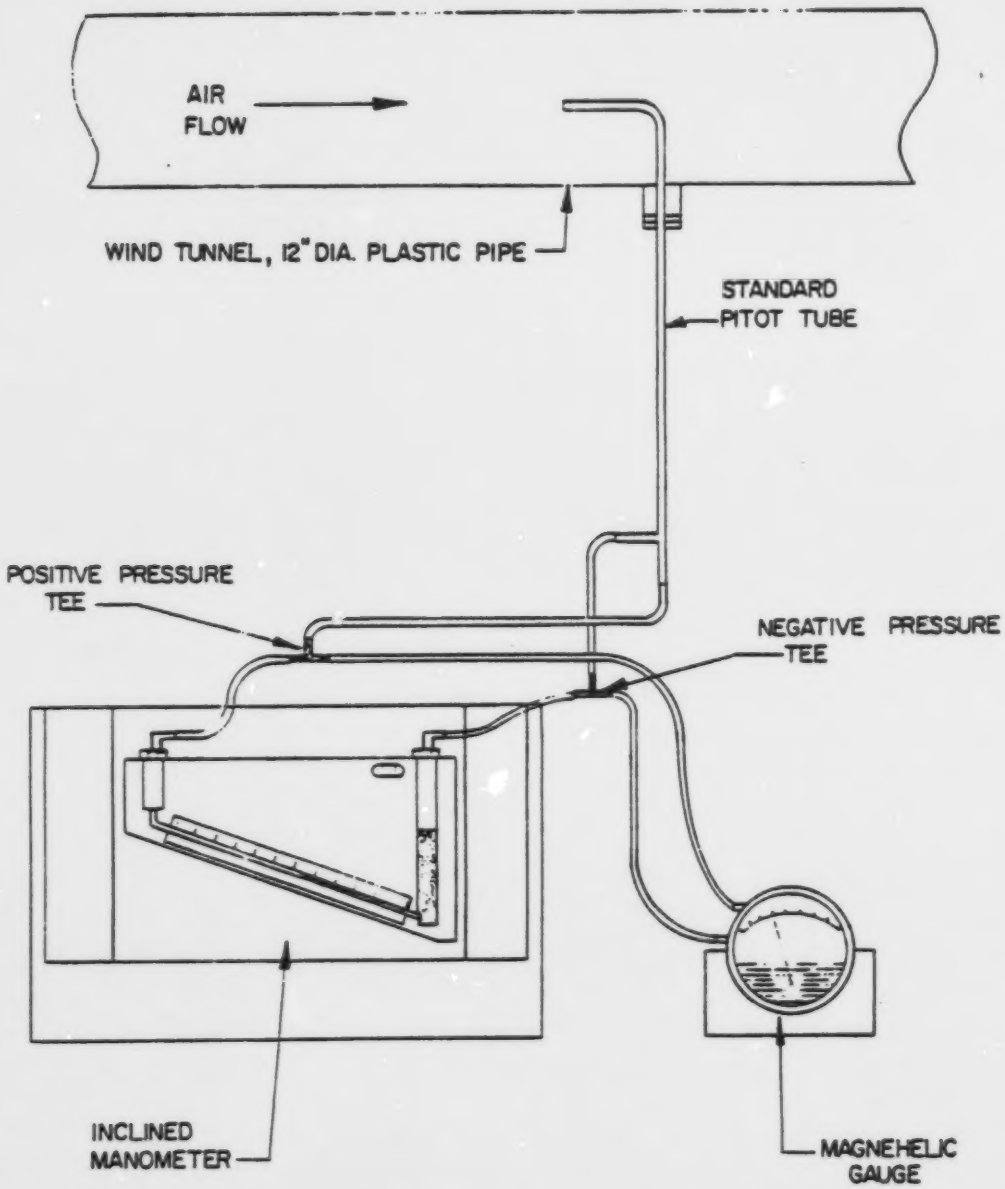


FIGURE 33

MAGNEHELIC GAUGE CALIBRATION FORM

Gauge Identification _____

Gauge Range _____ "H_2O

Present Use _____

Calibrated Vertically, Horizontally

DATE	RANGE	ΔP STD	ΔP MAG	% ERROR	COMMENTS
	1 2 3 AVG.	--	--		
	1 2 3 AVG.	--	--		
	1 2 3 AVG.	--	--		
	1 2 3 AVG.	--	--		
	1 2 3 AVG.	--	--		
	1 2 3 AVG.	--	--		
	1 2 3 AVG.	--	--		
	1 2 3 AVG.	--	--		

7.6 Calibration of Temperature Control System

The digital display temperature indicator of the control unit and the various thermocouples can be checked by comparing their respective readings when the sampling train is at ambient temperature. All temperature readings for indicator positions, #1-stack, #2-probe, #3-impinger outlet, #4-orifice, #6-cyclone, #7-dry gas meter inlet and #8-dry gas meter outlet, should agree within $\pm$ 5°F of the ambient temperature. A suspect thermocouple can be checked by immersion in ice water. Erroneous readings will also be caused by a drop in line voltage of more than 10 volts .

The temperature controllers for the gas conditioning coil and filter assembly heaters are calibrated at both room temperature and a temperature of >200°C. First, calibrate each controller with the probe and cyclone heaters not in operation and second, with these heaters set at a temperature of >200°C.

To calibrate the gas conditioning coil temperature controller, assemble the probe, cyclone and coil together in the sample box. Circulate air at approximately 1 cfm through these train components with only the coil compartment heater on and measure the coil discharge air temperature with either a standard glass thermometer or a calibrated thermocouple. Adjust the coarse and fine controls of the coil temperature controller until the temperature of the air leaving the coil is 200°C. Repeat this procedure with both the probe and cyclone heaters set at a temperature of >200°C and the coil heater in operation. No adjustment of the controller should be necessary.

To calibrate the filter-orifice temperature controller, assemble the probe, cyclone, gas conditioning coil, filter and orifice plate assemblies in the sample box. Circulate air at approximately 1 cfm through these train components with only the filter compartment heater on and measure the air temperature in the orifice assembly using the orifice thermocouple. Adjust the coarse and fine controls of the temperature controller until the orifice air flow temperature is 200°C. Repeat this procedure with the probe and cyclone heaters set at a temperature of >200°C and the coil and filter heaters in operation. No adjustment of the controller should be necessary.

A detailed description of the operation and calibration of the RFL temperature controller is included as Appendix J.

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APPENDIX A

STANDARD REFERENCE METHODS FOR SOURCE TESTING: EPS 1-AP-74-1

Environment Canada
Environmental Protection Service

Environnement Canada
Service de la protection de l'environnement

Standard Reference Methods for Source Testing: Measurement of Emissions of Particulates from Stationary Sources

REPRINT

Regulations, Codes, and Protocols
Report EPS 1-AP-74-1

Air Pollution
Control Directorate
February 1974

STANDARD REFERENCE METHODS FOR SOURCE TESTING: MEASUREMENT OF EMISSIONS OF PARTICULATES FROM STATIONARY SOURCES

Air Pollution Control Directorate
Environmental Protection Service

Report EPS 1-AP-74-1
February 1974

FOREWORD

The six test methods (A to F) presented in this report are used in various combinations to determine particulate emissions from stationary sources. The combination of test methods to be used for a specific source will be prescribed in guidelines and regulations applicable to the source. The test methods may also be used independently to determine certain characteristics of a gas stream, e.g. gas velocity and flow rate, moisture content, or gas density.

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1 METHOD A: DETERMINATION OF SAMPLING SITE AND TRAVERSE POINTS

1.1 Principle

A sampling site and the number of traverse points are selected to optimize the extraction of a representative sample.

1.2 Procedure

1.2.1 Selection of Sampling Site and Minimum Number of Traverse Points.

1.2.1.1 Select for a sampling site any cross section of the stack or duct that is at least eight stack or duct diameters downstream and two diameters upstream from any flow disturbance such as a bend, expansion, contraction, visible flame, or stack exit (see inset, Figure A-1). For rectangular cross sections the larger dimension shall be used to represent the stack diameter.

1.2.1.2 When the above sampling site criteria can be met, determine the minimum number of traverse points required from Table A-1. The minimum required number of traverse points is a direct function of stack or duct diameter.

1.2.1.3 When a sampling site such as described in section 1.2.1.1 is not accessible, choose a convenient sampling location and use Table A-1 and Figure A-1 to determine the minimum required number of traverse points. First, measure the distance from the chosen sampling location to the nearest upstream and downstream disturbances. Then, from Figure A-1 determine the corresponding sample point multiples for both distances and select the greater of these. Multiply it by the number obtained from Table A-1. The result of this calculation is the minimum number of traverse points required. This number may have to be increased such that for circular stacks the number is a multiple of 4 and for rectangular stacks the number follows the criteria of section 1.2.2.2.

1.2.2 Cross-Sectional Layout and Location of Traverse Points

1.2.2.1 For circular stacks divide the cross section into equal parts by two right-angle diameters. Locate half the traverse points symmetrically along each diameter according to Figure A-2 and Table A-2.

1.2.2.2 For rectangular stacks divide the cross section into as many equal rectangular areas as there are traverse points such that the ratio of the length to the width of the elemental area is between one and two. Locate the traverse points at the centroid of each area according to Figure A-2.

1.2.2.3 Under no conditions shall a sampling point be selected within 1 in. of the stack wall.

TABLE A-1 MINIMUM REQUIRED NUMBER OF TRAVERSE POINTS FOR SAMPLING SITES WHICH MEET SPECIFIED CRITERIA*

Inside diameter of stack or duct (ft)	Number of points
I.D. ≤ 1	4
1 < I.D. ≤ 2	8
2 < I.D. ≤ 4	12
4 < I.D. ≤ 8	20
8 < I.D. ≤ 16	32
16 < I.D.	Refer to Environment Canada before testing

*This table shall be used as described in section 1.2.1

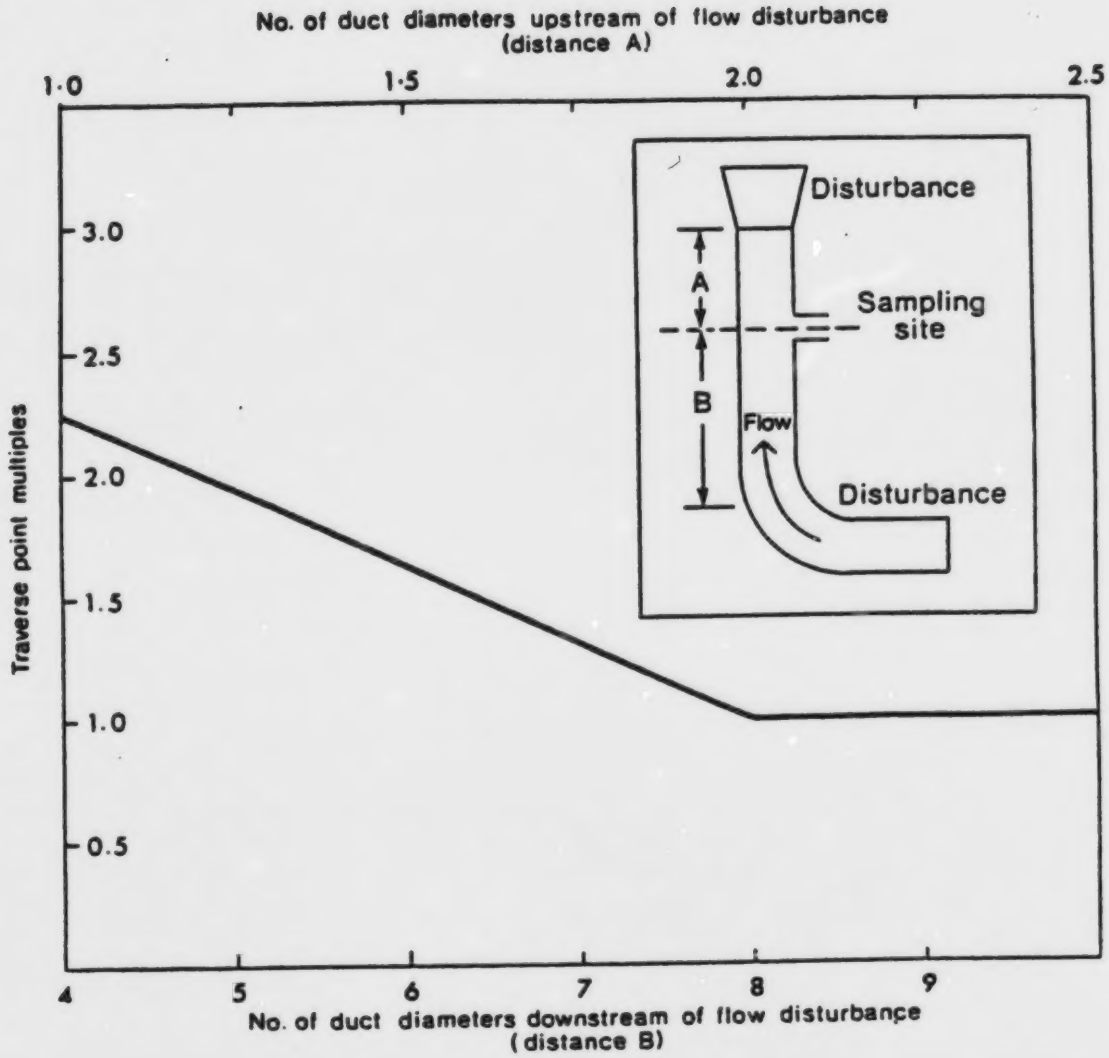
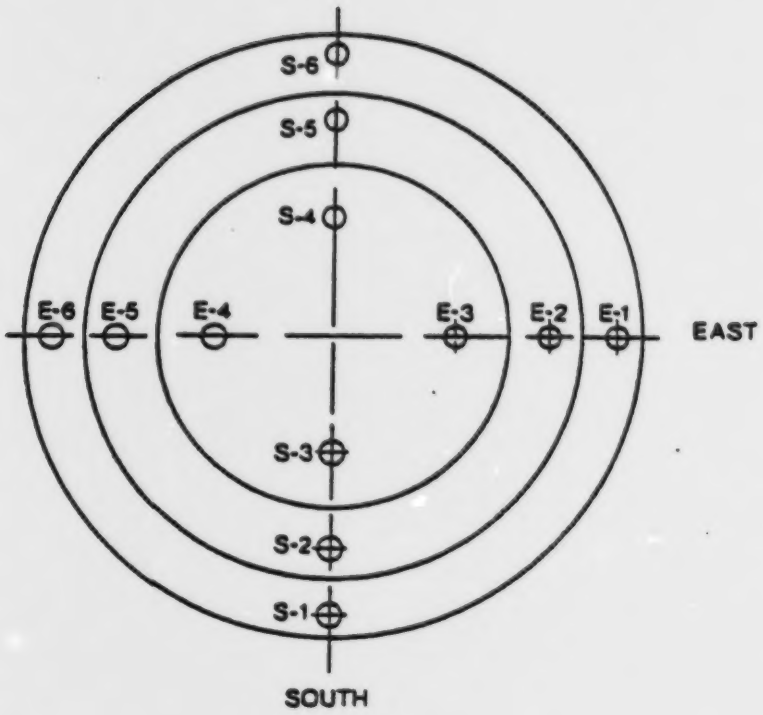


FIGURE A-1 TRAVERSE POINT MULTIPLES TO DETERMINE MINIMUM NUMBER OF TRAVERSE POINTS REQUIRED WHEN A < 2 OR B < 8

When A < 1 or B < 4 refer to Environment Canada before testing



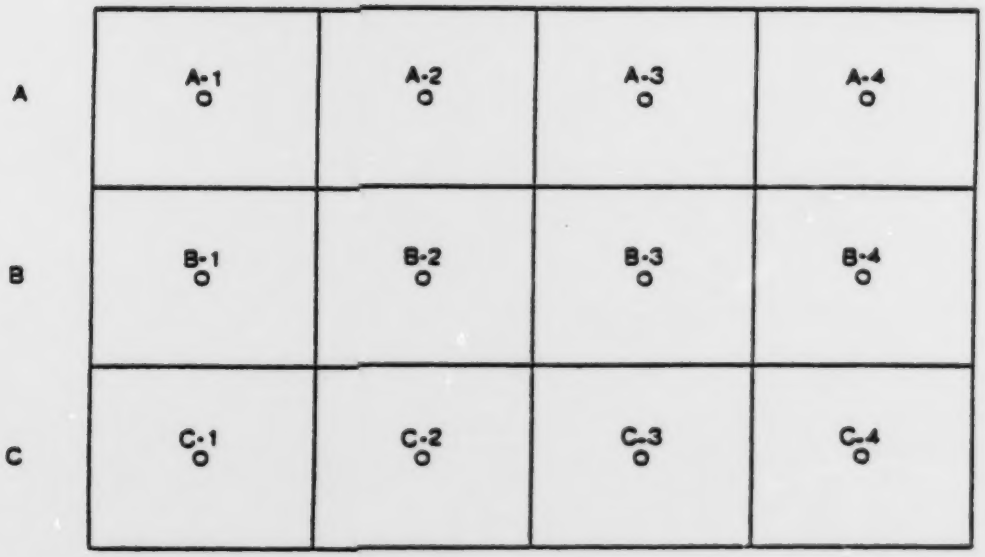


FIGURE A-2 LOCATION OF TRAVERSE POINTS ON CIRCULAR AND RECTANGULAR CROSS SECTIONS DIVIDED INTO 12 EQUAL AREAS

TABLE A-2 LOCATION OF TRAVERSE POINTS ON DIAMETERS OF CROSS SECTIONS OF CIRCULAR STACKS

TRAVERSE POINT NUMBER ON A DIAMETER	PERCENT OF STACK DIAMETER FROM INSIDE WALL TO TRAVERSE POINT											
	Number of traverse points on a diameter											
	2	4	6	8	10	12	14	16	18	20	22	24
1	14 6	6.7	4.4	3.3	2 5	2 1	1 8	1.6	1.4	1 3	1.1	1 1
2	85 4	25.0	14 7	10 5	8 2	6.7	5.7	4.9	4.4	3.9	3.5	3.2
3		75 0	29.6	19.4	14 6	11.8	9.9	8.5	7.5	6.7	6.0	5.5
4		93.3	70.5	32 3	22 6	17 7	14.6	12.5	10.9	9 7	8.7	7.9
5			85.3	67.7	34 2	25 0	20.1	16.9	14.6	12.9	11.6	10.5
6			95 6	80 6	65 8	35 5	26.9	22.0	18 8	16.5	14.6	13.2
7				89 5	77 4	64 5	36 6	28.3	23 6	20 4	18 0	16.1
8				96 7	85 4	75 0	63 4	37.5	29.6	25.0	21.8	19 4
9					91 8	82 3	73 1	62.6	38 2	30.6	26 1	23 0
10					97 5	88 2	79 9	71.7	61.8	38.8	31 5	27 2
11						93 3	85 4	78.0	70.4	61 2	39 3	32 3
12						97 9	90.1	83.1	76.4	69 4	60 7	39 8
13							94 3	87.5	81 2	75.0	68.5	60.2
14							98.2	91.5	85 4	79.6	73.9	67.7
15								95 1	89 1	83 5	78 2	72 8
16								98.4	92 5	87.1	82.0	77.0
17									95 6	90.3	85.4	80.6
18									98.8	93.3	88 4	83.9
19										96.1	91 3	86 8
20										98.7	94.0	89.5
21											96 5	92 1
22											98 9	94.5
23												96 8
24												98 9

2 METHOD B: DETERMINATION OF STACK GAS VELOCITY AND VOLUMETRIC FLOW RATE

2.1 Principle

2.1.1 Stack gas velocity is determined from gas density and from measurement of velocity pressure with an S-type (Stauscheibe or reverse type) pitot tube. A standard pitot tube may be used in clean gas streams where plugging of the tube openings is not likely to occur.

2.1.2 Stack gas volumetric flow rate is determined from measurements of stack gas velocity, temperature, absolute pressure, dry gas composition, moisture content, and stack diameter.

2.2 Apparatus

2.2.1 ***S-Type Pitot (Figure B-1).*** The S-type pitot tube is used to measure stack gas velocity and static pressures. The pitot tube coefficient must be within ±5% over the working range.

2.2.2 ***Standard Pitot.*** A standard pitot tube is required for calibrating the S-type pitot tube and can also be used for measuring velocity pressure in clean gas streams.

2.2.3 ***Differential Pressure Gauge.*** An inclined manometer or equivalent capable of measuring velocity pressure to within 0.005 in. H_2O shall be used.

2.2.4 ***Temperature Gauge.*** A thermocouple or equivalent capable of measuring stack temperature to within 1.5% of the minimum absolute stack temperature is required. When stack temperatures exceeding 700 °F are encountered, appropriate shielding and aspiration shall be provided for the thermocouple. The temperature and corrosiveness of the stack gases will determine the type of thermocouple to be used. The thermocouple is attached to the pitot tube as shown in Figure B-1.

2.2.5 ***Barometer.*** A barometer capable of measuring atmospheric pressure to within 0.1 in. Hg is needed.

2.2.6 ***Gas Analyzer.*** An analyzer capable of determining molecular weight on a dry basis within ±0.5% is required to determine stack gas composition.

2.3 Procedure

2.3.1 Set up the apparatus as shown in Figure B-1 using an S-type pitot tube that has been calibrated according to method F. Ensure that all connections are tight and leak free. Measure the velocity pressure and temperature concurrently at the traverse points specified by method A. Record these measurements on the velocity traverse data sheet (Figure B-2).

2.3.2 Measure the static pressure in the stack by disconnecting one leg of the pitot tube from the manometer and then rotating the assembly until the openings in the pitot tube are perpendicular to the gas flow. Record the manometer reading on the velocity traverse data sheet (Figure B-2).

2.3.3 Determine the stack gas molecular weight by gas analysis and appropriate calculations as indicated in method C.

2.4 Calculations

2.4.1 ***Average Stack Gas Velocity.*** Use Equation B-1 to calculate the average stack gas velocity at each traverse point:

$$[B-1] \qquad U_s = K_p\, C_p\, (\Delta p)^{1/2} \left(\frac{T_s}{P_s\ \ M_s} \right)^{1/2}$$

where

U_s - stack gas velocity, ft/s

K_p - constant, 85.33 $\left(\frac{\text{lb-in. Hg}}{\text{lb-mole °R in. } H_2O} \right)^{1/2}$ (ft/s)

C_p - S-type pitot tube coefficient

T_s - Absolute stack gas temperature, °R

(Δp) - stack gas velocity pressure, in. H_2O

P_s - absolute stack gas pressure, in. Hg

M_s - molecular weight of stack gas on wet basis (see Equation C-3), lb/lb-mole

2.4.2 ***Stack Gas Volumetric Flow Rate.*** Use Equation B-2 to calculate the stack gas volumetric flow rate.

$$[B-2] \quad Q_s = 3600\, (U_p)_{avg}\, A_s\, (1 - B_{ws}) \left(\frac{T_{std}}{(T_p)_{avg}} \right) \left(\frac{P_s}{P_{std}} \right)$$

where

Q_s - volumetric stack gas flow rate on dry basis at reference conditions, ft^3/h

$(U_s)_{avg}$ - average stack gas velocity, ft/s

A_s - cross-sectional area of duct or stack, ft^2

B_{wo} - proportion by volume of water vapour in stack gas

T_{ref} - absolute temperature at reference conditions, 537 °R

$(Ts)_{avg}$ - average absolute stack gas temperature, °R

P_s - absolute stack gas pressure, in. Hg

P_{ref} - absolute pressure at reference conditions, 29.92 in. Hg

3600 - conversion factor, s/h

NOTE - $(U_s)_{avg}$ is calculated by averaging the stack gas velocities measured at each traverse point.

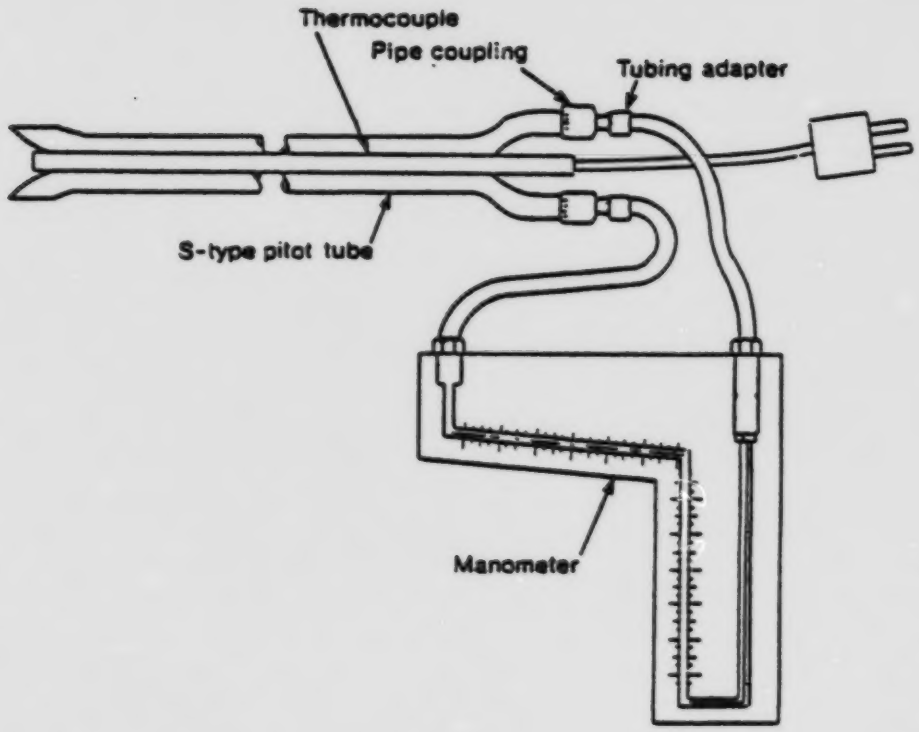


FIGURE B-1 S-TYPE PITOT TUBE AND MANOMETER ASSEMBLY

FIGURE B-2 VELOCITY TRAVERSE DATA SHEET

Plant _____ Stack dia. (in.) _____
Location _____ Barometric press. (in. Hg) _____
Test _____ Static press. in stack (in. H_2O) _____
Date _____ S-type pitot coefficient _____
Time started _____ Test conducted by _____
Time completed _____

Traverse point	Stack gas velocity pressure Δp (in. H_2O)	$(\Delta p)^{1/2}$	Stack gas temperature (°F)
		Average	

3 METHOD C: DETERMINATION OF MOLECULAR WEIGHT BY GAS ANALYSIS

3.1 Principle

An integrated or grab gas sample is extracted from a sampling point and analyzed for its components using an Orsat analyzer, a portable gas chromatograph, or equivalent.

3.2 Apparatus

3.2.1 Grab Sample Train (Figure C-1)

3.2.1.1 Probe. A stainless-steel or Pyrex probe equipped with a filter to remove particulate matter is required.

3.2.1.2 Pump. A one-way squeeze bulb pump or equivalent is used to transport the gas sample to the analyzer.

3.2.2 Integrated Sample Train (Figure C-2)

3.2.2.1 Probe. A stainless-steel or Pyrex probe equipped with a filter to remove particulate matter is used.

3.2.2.2 Condenser. An air-cooled condenser or equivalent to remove any excess moisture is required.

3.2.2.3 Needle valve. A valve to adjust flow rate is required.

3.2.2.4 Pump. A leak-free diaphragm-type pump or equivalent is used to pull gas through the sample train.

3.2.2.5 Rate meter. A meter capable of measuring a flow range from 0 to 0.035 ft^3/min is required.

3.2.2.6 S-type pitot tube. An S-type pitot tube or equivalent is attached to the probe so that the sampling flow rate can be regulated proportional to the stack gas velocity when velocity is varying with time or a sample traverse is conducted.

3.2.2.7 Flexible bag. A flexible bag of nonreactive material such as Tedlar or equivalent with a capacity of 2-3 ft^3 is required.

3.2.3 Analysis

An Orsat analyzer, portable gas chromatograph, or equivalent is needed.

3.3 Procedure

3.3.1 Grab Sampling

3.3.1.1 Set up the equipment as shown in Figure C-1 ensuring that all connections are leak free. Place the probe in the stack at a sampling point and purge the sampling line.

3.3.1.2 Draw a sample into the analyzer.

3.3.2 Integrated Sampling

3.3.2.1 Evacuate the flexible bag. Assemble the equipment as shown in Figure C-2 with the bag disconnected. Place the probe in the stack and purge the sampling line. Connect the bag, ensuring that all connections are tight and leak free.

3.3.2.2 Sample at a rate proportional to the stack gas velocity. Proportional sampling is defined as sampling at a rate such that the velocity (V_n) of the sample through the nozzle is proportional to the velocity in the stack (V_s) at the sampling point, or $V_n = K V_s$. Any change in the stack gas velocity necessitates a change in the sampling rate to maintain the originally established proportionality constant K.

3.3.3 Analysis

3.3.3.1 Determine the gaseous concentrations as soon as possible after sampling.

3.3.3.2 For grab sampling, repeat the sampling and analysis until three consecutive samples vary no more than 0.5% by volume for each component being analyzed.

3.3.3.3 For integrated sampling, repeat the analysis of the sample until three consecutive analyses vary no more than 0.2% by volume for each component being analyzed.

3.4 Calculations

3.4.1 ***Average Molecular Weight.*** The average molecular weight of the gas mixture is described by the expression:

$$M = \sum_{i=1}^{n} x_i M_i$$

where x_i is the mole fraction and M_i the mole weight of each constituent in the mixture.

3.4.2 ***Dry and Wet Molecular Weights.*** For the majority of sources, use Equation C-1 to calculate the dry molecular weight of the sample. This equation may be modified with additional terms if other gaseous constituents that will influence the molecular weight of the sample are present. Use Equation C-2 to calculate the molecular weight of the stack gas on a wet basis.

[C-1] $M_d = 0.44(\%CO_2) + 0.32(\%O_2) + 0.28(\%N_2 + \%CO)$

[C-2] $M_s = M_d(1 - B_{wo}) + 18B_{wo}$

where

M_d - molecular weight of stack gas on dry basis, lb/lb-mole

M_s - molecular weight of stack gas on wet basis, lb/lb-mole

$\%CO_2$ - percent carbon dioxide by volume, dry basis

$\%O_2$ - percent oxygen by volume, dry basis

$\%N_2$ - percent nitrogen by volume, dry basis

0.44 - molecular weight of carbon dioxide divided by 100, lb/lb-mole

0.32 - molecular weight of oxygen divided by 100, lb/lb-mole

0.28 - molecular weight of nitrogen and carbon monoxide divided by 100, lb/lb-mole

B_{wo} - proportion by volume of water vapour in stack gas

18 - molecular weight of water, lb/lb-mole

NOTE - $\%N_2$ is calculated using the difference method. In the majority of cases the following equation may be used:

$$\%N_2 = 100 - (\%CO_{2avg} + \%O_{2avg} + \%CO_{avg})$$

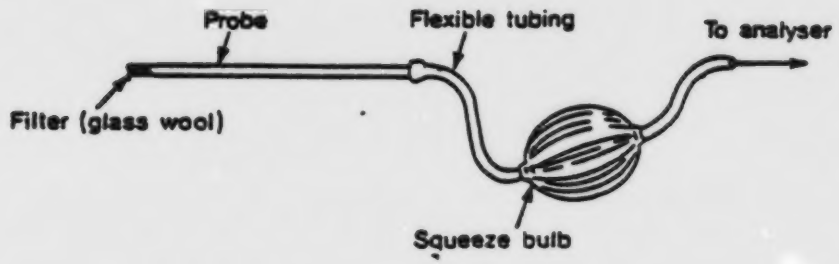


FIGURE C-1 GRAB SAMPLE TRAIN

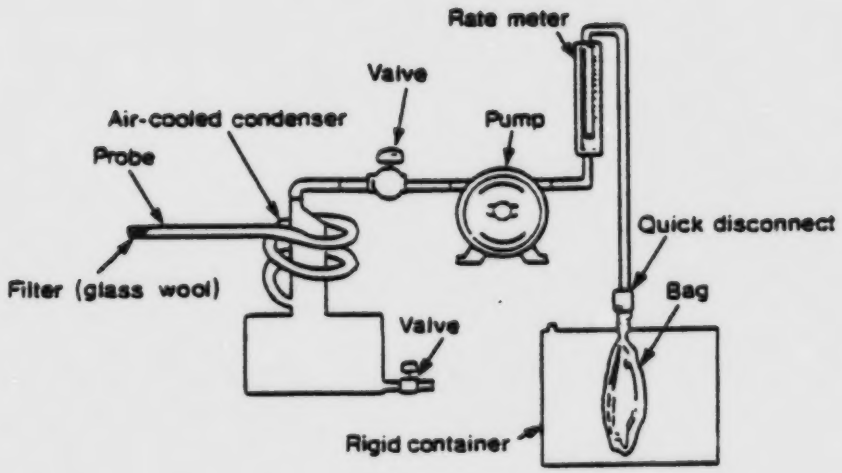


FIGURE C-2 INTEGRATED SAMPLE TRAIN

4 METHOD D: DETERMINATION OF MOISTURE CONTENT

4.1 Principle

Moisture is removed from the gas stream, condensed, and measured volumetrically. If the presence of liquid droplets is suspected, the moisture content determined using this method should be compared with psychrometric charts to ensure that moisture levels greater than saturated conditions are not reported for the average stack gas temperature. If stack gas temperature is less than 212 °F and stack gas velocity is greater than 15 ft/s, the wet bulb - dry bulb technique may be used to determine moisture content, except for acid gas streams.

4.2 Apparatus

4.2.1 ***Probe.*** A stainless-steel or Pyrex probe sufficiently heated to prevent condensation and equipped with a filter to remove particulate matter is required.

4.2.2 ***Impingers.*** Two midget impingers each with 30 ml capacity or equivalent are required.

4.2.3 ***Ice Bath Container.*** An ice bath to condense moisture in impingers is used.

4.2.4 ***Silica Gel Tube (Optional).*** This tube is used to protect the pump and dry gas meter.

4.2.5 ***Flow Control Valve.*** A valve is needed to regulate gas flow.

4.2.6 ***Pump.*** A leak-free pump is required to pull gas through the train.

4.2.7 ***Dry Gas Meter.*** A calibrated dry gas meter capable of measuring to within 1% of the total sample volume is required.

4.2.8 ***Rotameter.*** A rotameter or orifice meter calibrated to measure up to a maximum flow of 0.2 ft^3/min is needed.

4.2.9 ***Graduated Cylinder.*** A 25 ml graduated cylinder is required.

4.2.10 ***Barometer.*** A barometer capable of reading to within 0.1 in. Hg is required.

4.2.11 ***S-Type Pitot Tube.*** An S-type pitot tube or equivalent is attached to the probe so that the sampling flow rate can be regulated proportionally to the stack gas velocity when velocity is varying with time or a sample traverse is conducted.

4.3 Procedure

4.3.1 Place exactly 5 ml distilled water in each impinger. Assemble the apparatus without the probe as shown in Figure D-1. Test for leaks by plugging the inlet to the first impinger and drawing a vacuum.

4.3.2 Connect the probe and sample at 0.075 ft^3/min. Adjust the sampling rate proportionally to any changes in stack gas velocity. Continue sampling until the dry gas meter registers 1 ft^3 or until

visible liquid droplets are carried over from the first impinger to the second. Record temperature, pressure, and dry gas meter readings and tabulate using Figure D-2.

4.3.3 After collecting the sample, measure the volume increase to the nearest 0.5 ml.

4.4. Calculations

4.4.1 ***Volume of Water Vapour Collected.*** Use Equation D-1 to calculate the volume of water vapour collected.

[D-1]] $$V_{wc} = \frac{(V_f - V_i)\ \ rH_2O\ RT_{ref}}{(453.59)\ P_{ref}\ M_{H2O}}$$

$$= 0.0480\ ft^3/ml\ (V_f - V_i)$$

where

V_{wc} - volume of water vapour collected at reference conditions, ft^3

V_f - final volume of impinger contents, ml

V_i - initial volume of impinger contents, ml

453.59 - conversion factor, g/lb

R - ideal gas constant, 21.83 (in. Hg ft^3) (lb-mole °R)

rH_2O - density of water, 1 g/ml

T_{ref} - absolute temperature at reference conditions, 537 °R

P_{ref} - absolute pressure at reference conditions, 29.92 in. Hg

M_{H2O} - molecular weight of water, 18 lb/lb-mole

4.4.2 ***Gas Volume.*** Use Equation D-2 to calculate gas volume.

[D-2]] $$(V_m)_{ref} = V_m \left(\frac{P_m}{P_{ref}}\right) \left(\frac{T_{ref}}{T_m}\right)$$

$$= 17.95\ \frac{°R}{in.Hg}\ \frac{V_m\ P_m}{T_m}$$

where

$(V_m)_{ref}$ - dry gas volume through dry gas meter at reference conditions, ft^3

V_m - dry gas volume measured by dry gas meter, ft^3

P_m - absolute pressure at the dry gas meter, in. Hg

P_{ref} - absolute pressure at reference conditions, 29.92 in. Hg

T_m - absolute temperature at dry gas meter, °R

T_{ref} - absolute temperature at reference conditions, 537 °R

4.4.3 ***Moisture Content.*** Use Equation D-3 to calculate moisture content.

[D-3] $$B_{wo} = \frac{V_{wc}}{V_{wc} + (V_m)_{ref}} + B_{wm}$$

$$B_{wm} = \frac{P_v}{P}$$

where

B_{wo} - proportion by volume of water vapour in the gas stream

V_{wc} - volume of water vapour collected at reference conditions, ft^3

$(V_m)_{ref}$ - dry gas volume through dry gas meter at reference conditions, ft^3

B_{wm} - volumetric proportion of water vapour in the gas stream leaving the last impinger

P_v - partial pressure of water vapour leaving the last impinger, in. Hg

P - absolute pressure at last impinger; may be approximated by the barometric pressure, in. Hg

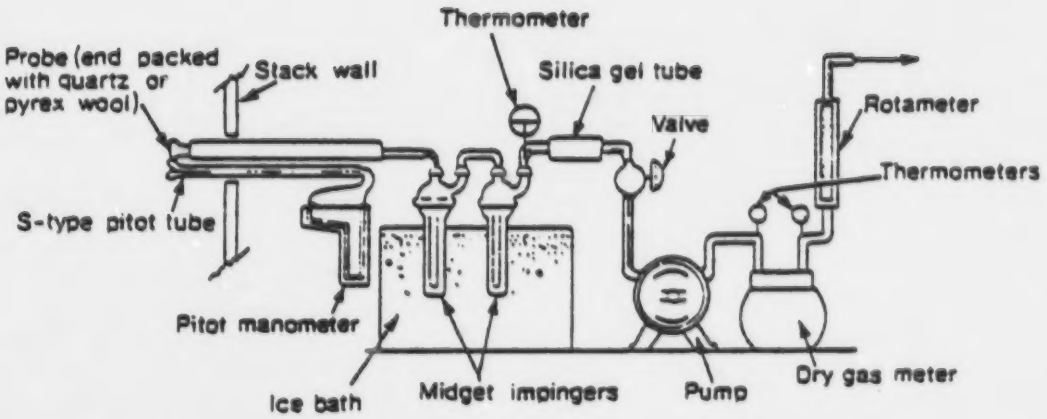


FIGURE D-1 MOISTURE SAMPLING TRAIN

FIGURE D-2 MOISTURE DATA SHEET

Plant _____

Location _____

Test _____

Date _____

Barometric pressure, in. Hg _____

Volume of moisture condensed, ml _____

Test conducted by _____

Time	Meter volume (ft^3)	Meter temp. (°F)		Last impinger temp. (°F)	Rotameter reading (ft^3/min)
		Inlet	Outlet		

5 METHOD E: DETERMINATION OF PARTICULATE EMISSIONS

5.1 Principle

Particulate matter is withdrawn isokinetically from a number of sampling points in the stack and its weight determined gravimetrically after removal of uncombined water. Sampling isokinetically means that the linear velocity of the gas entering the sampling nozzle is equal to that of the undisturbed gas stream at the sample point.

5.2 Apparatus

5.2.1 Sampling Train (Figure E-1)

5.2.1.1 Nozzle. A stainless-steel nozzle with sharp, tapered leading edge is required. An equivalent nozzle made of Pyrex, Vycor, borosilicate, or quartz may be used when high temperature or corrosive gases are encountered.

5.2.1.2 Probe. A Pyrex probe encased in stainless-steel tubing with a heating system capable of maintaining a gas temperature in excess of the acid dewpoint or 250 °F, whichever is greater, at the exit end during sampling to prevent condensation is required. Probes for sampling gas streams in excess of 600 °F shall be constructed of special glass liners such as Vycor, quartz, or equivalent material. Where length or strength limitations preclude the use of a glass liner, Incoloy 825 or equivalent may be used. Water-cooled probes may be used where very hot gases capable of damaging the nozzle-probe assembly are encountered.

5.2.1.3 S-Type pitot tube. An S-type pitot tube or equivalent is attached to the probe to monitor stack gas velocity.

5.2.1.4 Temperature gauge. A thermocouple or equivalent capable of measuring stack temperatures to within 1.5% of the minimum absolute stack temperature is attached to the pitot tube. When stack temperatures exceeding 700 °F are encountered, appropriate shielding and aspiration shall be provided for the thermocouple. The temperature and corrosiveness of the stack gases will determine the type of thermocouple to be used.

5.2.1.5 Miniature cyclone (optional). A Pyrex miniature cyclone following the sampling probe and preceding the filter is used to collect the large-particulate fraction in gas streams when appreciable. The cyclone prevents the premature build-up of particulate matter on the filter medium and permits longer sampling runs than can be achieved without it. The cyclone must be maintained at a temperature in excess of the acid dewpoint of the gas sampled or 225 °F, whichever is greater.

5.2.1.6 Filter holder. A Pyrex filter holder with a heating system capable of maintaining a temperature in excess of the acid dewpoint of the gas sampled or 225 °F, whichever is greater, is required. A filter support of porous fritted glass material or equivalent and a suitable gasket shall be used.

5.2.1.7 Filter. A flash-fired glass fibre filter (organic binder removed) of a diameter compatible with the filter holder and of 0.3 mm porosity is needed. Other types of filter media may be used depending on the type, size, and amount of particulate matter, the temperature and corrosive constituents in the stack gases, and the subsequent analysis required.

5.2.1.8 Impingers. Four Greenburgh-Smith impingers are connected in series. The first, third, and fourth impingers are modified by replacing the tips and impaction plate of the standard design with a 1/2 in. I.D. glass tube extending to 1/2 in. from the bottom of the flask. The second impinger has the standard tip and impaction plate.

5.2.1.9 Leakless vacuum pump. A vacuum pump capable of maintaining an isokinetic sampling rate and continuously withdrawing a portion of the stack gases through the sampling train is used. The pump is connected to the outlet of the last impinger by a vaccum line containing a vacuum gauge to measure the pump intake vacuum to within 0.5 in. Hg and a coarse adjust valve to regulate sample flow. A bypass valve is connected across the vacuum pump to allow for fine control of the sample flow.

5.2.1.10 Dry gas meter. A dry gas meter calibrated to within ±1% and equipped with inlet and outlet temperature indicators is used to determine sample volume. The dry gas meter follows the vacuum pump in the sampling train.

5.2.1.11 Orifice meter. A calibrated orifice meter is used to measure the sample flow rate. The orifice meter is connected to the outlet of the dry gas meter.

5.2.1.12 Differential pressure gauges. Inclined manometers or equivalent capable of measuring pitot tube velocity pressure and the pressure drop across the orifice meter to within 0.005 in. H_2O are required.

5.2.1.13 Barometer. A barometer capable of measuring atmospheric pressure to ±0.1 in. Hg shall be used.

5.2.2 Sample Recovery

5.2.2.1 Probe brush. A brush at least as long as the probe is required.

5.2.2.2 Miscellaneous. Two wash bottles, sample storage containers, and a 250 ml graduated cylinder are required.

5.2.3 Sample Analysis

5.2.3.1 Trip balance. A 300 g capacity balance capable of measuring to ±0.05 g is required.

5.2.3.2 Analytical balance. A balance capable of measuring to ±0.1 mg shall be used.

5.2.3.3 Miscellaneous. Glass weighing dishes and a desiccator are required.

5.3 Reagents

5.3.1 Sampling Train. Indicating-type 6-16 mesh silica gel dried at 350 °F for 2 h, deionized or distilled water, and crushed ice are required.

5.3.2 Sample Recovery. Reagent-grade, acetone and deionized or distilled water are required.

5.3.3 Sample Analysis. Deionized or distilled water is required.

5.4 Procedure

5.4.1 Sampling Train

5.4.1.1 Preliminary. Select the sampling site and minimum number of sampling points according to procedures described in method A. Determine the stack pressure, temperature, moisture, and range of velocity pressures, and use this information to calculate the required isokinetic sampling flow rate during subsequent stack-sampling tests. Determine the size of nozzle required for isokinetic sampling using these data. Recommended minimum nozzle size is 1/4 in. I.D.

5.4.1.2 Preparation of collection train. Label a filter of proper diameter, desiccate for at least 24 h using Drierite or equivalent at 70 ± 10 °F, and weigh to the nearest 0.5 mg in a room where the relative humidity is less than 50%. The preweighed filter should be placed in a clean container to prevent contamination during transportation to the sampling site. Weigh to the nearest gram approximately 200 g of silica gel. Place 100 ml of deionized or distilled water in each of the first two impingers, leave the third impinger empty, and place approximately 200 g of preweighed silica gel in the fourth impinger. Set up the sampling train without the probe as in Figure E-1. Check the sampling train at the sampling site for leaks by plugging the inlet to the filter holder and pulling a 15 in. Hg vacuum. If the needle on the dry gas meter moves, a leakage rate not in excess of 0.02 ft^3/min at a vacuum of 15 in. Hg is acceptable. Attach the probe and adjust the heater to provide a minimum gas temperature of 250 °F at the probe outlet. Adjust the filter heating system to provide a temperature of 225 °F at the filter holder. Place crushed ice around the impingers. Add more ice during the run to keep the temperature of the gases leaving the last impinger as low as possible, preferably at 70 °F or less. Temperatures above 70 °F may result in damage to the dry gas meter from either moisture condensation or excessive heat.

5.4.1.3 Particulate train operation. To begin sampling, position the sampling nozzle at the first sampling point (traverse point). Point the nozzle directly into the approaching gas stream and secure the entire apparatus to the support system. Immediately start the vacuum pump and adjust the sampling flow rate to isokinetic conditions. Sample for at least 5 min at each sampling point; sampling time must be the same for each point. Maintain isokinetic sampling throughout the sampling period by making the necessary adjustments in the sampling flow rate as stack conditions change, or as the build-up of particulate matter on the filter affects the flow. Nomographs are available, or can be constructed, which aid in the rapid adjustment of the sampling rate without other computations. For each run, record the data required on the example sheet shown in Figure E-2. Instrument readings shall be recorded at intervals that are consistent with the time duration established for each point. For example, if testing for a minimum of 5 min per point, readings should be recorded every 2 1/2 min and whenever flow

adjustments are necessary. The time between readings should not exceed 5 min. When the traverse is completed, turn off the vacuum pump and record the final instrument readings. Transfer the sampling apparatus to the other sampling port and repeat the sampling procedure. When the second traverse is completed, remove the sampling apparatus from the stack and handle in accordance with the sample recovery procedure described in section 5.4.2.

5.4.2 Sample Recovery. At the sampling site, disconnect the probe from the sampling train. Exercise care in moving the collection train from the test site to the sample recovery area to minimize the loss of collected sample or the gain of extraneous particulate matter. Wash the interior surfaces of the nozzle-probe assembly with acetone using a brush to remove the particulate matter adhering to the walls, place these washings in a numbered container (container 1), and cover. If a miniature cyclone was used ahead of the filter, remove it from the collection train and wash the interior surfaces with acetone; use a rubber policeman to remove the particulate matter adhering to these surfaces, and add these washings to container 1. Remove the filter from its holder, transfer to its container, and seal. Wash the interior surfaces of the filter holder preceding the filter with acetone and add the washings to container 1. Seal this container. Measure the volume of water in the first three impingers to the nearest 0.5 ml and record the results on the moisture analysis data sheet (Figure E-3). Transfer the contents of the three impingers to a second numbered container (container 2). Rinse the first three impingers, all connectors, and the interior surface of the filter holder following the filter with deionized or distilled water and add these washings to container 2. Seal container 2. Using a rubber policeman if necessary, transfer the silica gel from the fourth impinger to a container and seal.

5.4.3 Sample Analysis

5.4.3.1 Nozzle-probe, cyclone, and filter holder washings. Transfer the contents of container 1 to a tared-glass beaker, cover with a watch glass, and evaporate to dryness at room temperature and pressure. Desiccate to a constant weight. Record results to the nearest 0.5 mg on the particulate matter analysis sheet (Figure E-4).

5.4.3.2 Cyclone collection flask. Desiccate the particulate matter in the collection flask to a constant weight and record the results to the nearest 0.5 mg on the particulate matter analysis sheet (Figure E-4).

5.4.3.3 Glass fibre filter. Transfer the filter and any loose particulate matter from the sample container to a tared-glass weighing dish. Desiccate to a constant weight and record the results to the nearest 0.5 mg on the particulate matter analysis sheet.

5.4.3.4 Impingers. Evaporate the contents of the impingers and impinger washings to dryness at 212 °F. Desiccate to a constant weight and record the results to the nearest 0.5 mg on the particulate matter analysis sheet. Do not include the weight of this material in the calculation of the total weight of particulate matter unless so specified in the definition of particulate matter for the facility being tested. Weigh the spent silica gel taken from the fourth impinger to the nearest gram and record the result on the moisture data sheet (Figure E-3).

5.5 Calculations

5.5.1 Average Dry Gas Meter Temperature and Average Orifice Pressure Drop. Refer to data sheet (Figure E-2).

5.5.2 Dry Gas Volume. Correct the sample volume measured to reference conditions (77 °F and 29.92 in. Hg) by using Equation E-1.

$$[E-1] \qquad (V_m)_{ref} = V_m \left(\frac{T_{ref}}{T_m}\right)\left(\frac{P_{bar} + \frac{\Delta H}{13.6}}{P_{ref}}\right)$$

$$(V_m)_{ref} = \left(17.95 \ \frac{°R}{\text{in. Hg}}\right)\left(\frac{V_m}{T_m}\right)\left(P_{bar} + \frac{\Delta H}{13.6}\right)$$

where

$(V_m)_{ref}$ – volume of gas through dry gas meter at reference conditions, ft^3

V_m – volume of gas measured by dry gas meter at meter conditions, ft^3

T_{ref} – absolute temperature at reference conditions, 537 °R

T_m – average dry gas meter temperature, °R

P_{bar} – barometric pressure, in. Hg

ΔH – average pressure drop across orifice (see Figure E-2), in. H_2O

13.6 – conversion factor, in. H_2O/in. Hg

P_{ref} – absolute pressure at reference conditions, 29.92 in. Hg

5.5.3 Volume of Water Vapour. Convert the volume of water condensed during the stack test to a volume of water vapour at reference conditions using Equation E-2.

$$[E-2] \qquad (V_w)_{ref} = V_{lc}\left(\frac{\rho H_2O}{M_{H_2O}}\right)\left(\frac{RT_{ref}}{P_{ref}}\right)\left(\frac{1}{453.59}\right)$$

$$(V_w)_{ref} = (0.0480 \ \frac{ft^3}{ml}) \ V_{lc}$$

where

$(V_w)_{ref}$ - volume of water vapour in gas sample at reference conditions, ft^3

V_{lc} - total volume of liquid collected in impingers (see Figure E-2), ml

ρH_2O - density of water, 1 g/ml

M_{H_2O} - molecular weight of water, 18 lb/lb-mole

R - ideal gas constant, 21.83 in. Hg ft^3/lb-mole °R

T_{ref} - absolute temperature at reference conditions, 537 °R

P_{ref} - absolute pressure at reference conditions, 29 92 in. Hg

453.59 - conversion factor, g/lb

5.5.4 ***Moisture Content.*** Calculate the moisture content of the stack gas using Equation E-3.

[E-3] $$B_{wo} = \frac{(V_w)_{ref}}{(V_m)_{ref} + (V_w)_{ref}}$$

where

B_{wo} - proportion by volume of water vapour in the gas stream

$(V_w)_{ref}$ - volume of water vapour in the gas sample at reference conditions (see Equation E-2), ft^3

$(V_m)_{ref}$ - volume of gas through dry gas meter at reference conditions, ft^3

5.5.5 ***Total Particulate Weight.*** Determine the total particulate catch from the sum of the weights on the analysis data sheet (Figure E-4).

5.5.6 ***Concentration of Particulate Matter.*** Determine the concentration of particulate matter in the stack gas using Equation E-4.

[E-4] $$C_s = (2.205 \times 10^{-6}) \frac{M_p}{(V_m)_{rel}}$$

where

C_s – concentration of particulate matter in stack gas on a dry basis at reference conditions, lb/ft³

M_p – total amount of particulate matter collected (see Figure E-4), mg

$(V_m)_{rel}$ – volume of gas sample through dry gas meter at reference conditions (see Equation E-1), ft³

2.205×10^{-6} – conversion factor, lb/mg

5.5.7 ***Emission Rate.*** Calculate the emission rate of particulate matter using Equation E-5.

[E-5] $$ER_p = (C_s)(Q_s)$$

where

ER_p – emission rate of particulate matter from the stack on a dry basis at reference conditions, lb/h

C_s – concentration of particulate matter in stack gas on a dry basis at reference conditions, lb/ft³

Q_s – volumetric stack gas flow rate on a dry basis at reference conditions (see Equation B-2), ft³/h

5.5.8 ***Acceptable Results.*** The isokinetic variation (I), calculated for each sample point using Equation E-6, should fall within the range $90\% \leq I \leq 110\%$.

[E-6] $$\%\ I = \frac{\frac{V_m}{t}\left(\frac{1}{1-B_{wo}}\right)\left(P_{bar} + \frac{\Delta H}{13.6}\right)T_s}{0.3272\ (N_d)^2\left(\frac{T_{mi} + T_{mo}}{2}\right)P_s\ U_s} \times 100$$

where

I	- ratio of the sampling velocity through the nozzle to stack gas velocity
V_m	- volume of gas sampled through gas meter at meter conditions for each point sampled. ft^3
t	- sampling time for each point sampled. min
B_{wo}	- proportion by volume of water vapour in the gas stream (see Equation E-3)
P_s	- absolute stack gas pressure. in. Hg
T_s	- absolute stack gas temperature for each point sampled. °R
T_{mi}	- dry gas meter absolute. inlet temperature for each point sampled. °R
T_{mo}	- dry gas meter absolute. outlet temperature for each point sampled. °R
P_{bar}	- barometric pressure at the sampling site. in. Hg
U_s	- stack gas velocity at each point sampled (see Equation B-1). ft/s
N_d	- inside diameter of sampling nozzle. in.
ΔH	- pressure drop across orifice meter for each point sampled. in. H_2O
0 3272	- conversion factor. (s/min) $(ft^2/in.^2)$
13 6	- conversion factor. in. H_2O/in. Hg

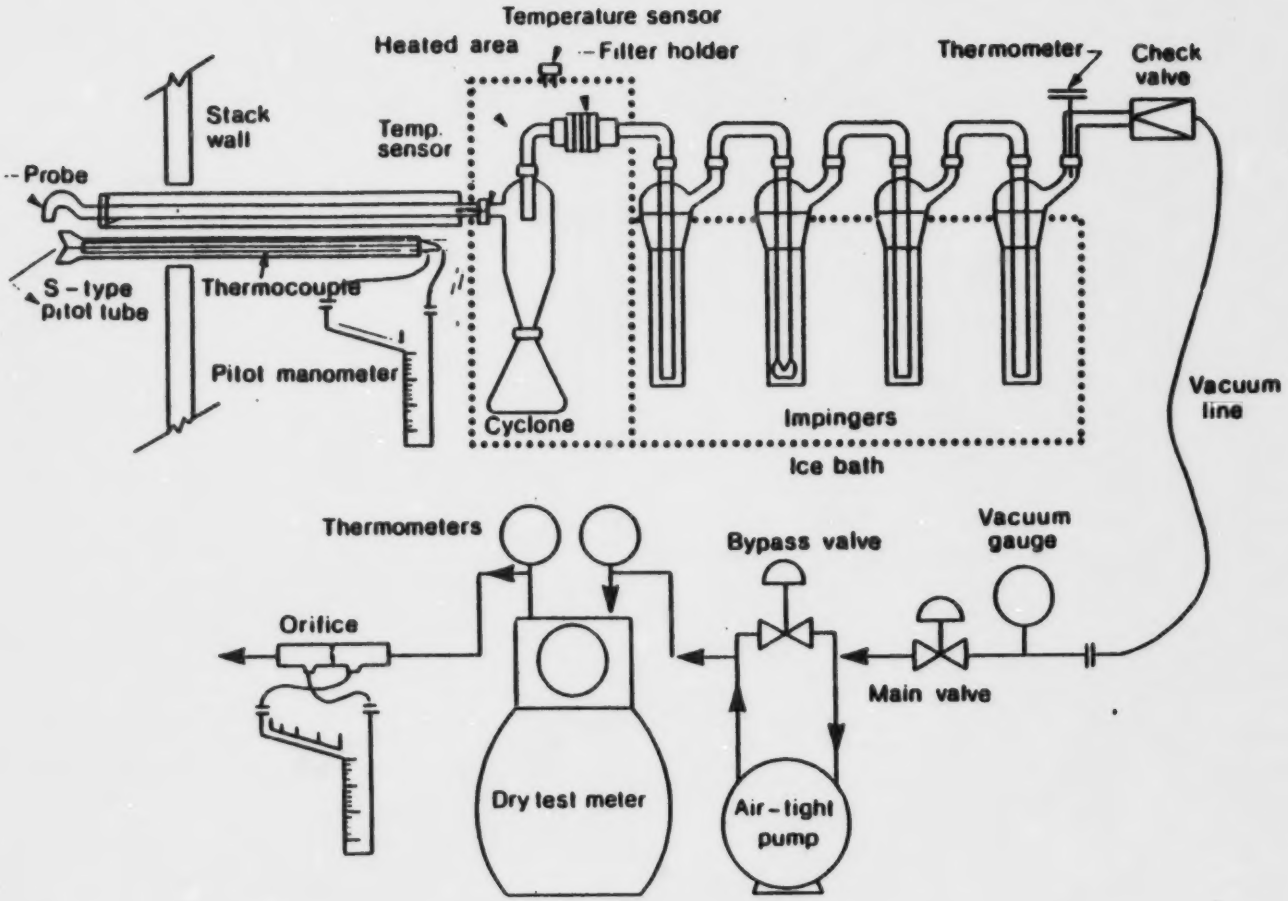


FIGURE E-1 PARTICULATE SAMPING TRAIN

FIGURE E-2 PARTICULATE FIELD DATA SHEET

Plant _____
Location _____
Test _____
Date _____
Ambient temperature, °F _____
Barometric pressure in. Hg _____
Assumed moisture content, % _____

Nozzle diameter, in _____
Probe length, ft _____
Probe temperature, °F _____
Filter holder temperature, °F _____
*Meter $\Delta H@$ _____
**C factor _____
Test conducted by _____

Traverse point	Time	Stack gas temp (°F)	Velocity pressure (in H_2O)	Orifice pressure drop (in H_2O)	Gas meter volume (ft^3)	Gas meter temp. (°F) Inlet	Gas meter temp. (°F) Outlet	Temp. of gas leaving last impinger (°F)	Pump intake vacuum (in. Hg)

*$\Delta H@$ is the orifice meter parameter defined in section 8.2.4.2
**C factor is determined from the nomograph.

FIGURE E-3 MOISTURE ANALYSIS DATA SHEET

Plant _____

Location _____

Test _____

Date _____

Test conducted by _____

	Impinger volume (ml)	Weight of silica gel (g)
Final Initial Liquid Collected		
Total volume collected	V_{lc}	ml*

*Volume of water, ml $= \frac{1 \text{ g/ml}}{\text{weight of water}}$

FIGURE E-4 PARTICULATE MATTER ANALYTICAL DATA SHEET

Plant _____

Location _____

Test _____

Date _____

Test conducted by _____

	Final weight (mg)	Tare weight (mg)	Weight of particulate matter (mg)
Container 1: Beaker containing washings from nozzle-probe, cyclone, front half of filter holder			
Container 2: Beaker containing impinger contents and washings from all connectors and back half of filter holder			
Cyclone collection flask			
Glass fibre filter			
	Total weight of particulate matter M_p (mg)		

*Not to be included in determination of the total weight of particulate matter (M_p) unless specified by the test procedure that applies.

6 METHOD F: CALIBRATION PROCEDURE FOR S-TYPE PITOT TUBE, DRY GAS METER, ORIFICE METER, AND ROTAMETER

6.1 S-Type Pitot Tube

6.1.1 ***Principle.*** The S-type pitot tube and probe assembly are calibrated against a standard pitot tube with known coefficient. Calibration shall be conducted before and after each field use and the coefficients recorded.

6.1.2 ***Apparatus***

6.1.2.1 *Standard pitot tube.* A standard pitot tube is used for calibrating the S-type pitot tube.

6.1.2.2 *Differential pressure gauge.* An inclined manometer or micromanometer is used to measure velocity pressure to within 0.005 in. H_2O.

6.1.2.3 *Flowing gas stream.* A flowing stream of gas within a wind tunnel or uniform straight duct is required

6.1.3 ***Procedure.*** Place the S-type pitot tube and probe assembly in the air stream near the center of the duct at least eight duct diameters upstream and two downstream from any point of disturbance. Record the velocity pressure first with one leg of the pitot tube orientated downstream and then with the other. Remove the S-type pitot tube and place a standard pitot tube at the same point and record the velocity pressure. Continue this procedure varying the velocity of the air stream until the expected working range of the pitot tube has been covered.

More elaborate procedures which allow the simultaneous reading of the S-type and standard pitot tube velocity pressures may be used providing the minimum requirements specified previously are met

6.1.4 ***Calculations.*** Calculate the pitot tube coefficient using Equation F-1. Compare the coefficients obtained with each orientation of the pitot tube. Use the pitot tube only if the coefficients differ by no more than 0.01, and if the average coefficient is within the range 0.85 ±0.02.

$$[F-1] \qquad C_{p\ test} = C_{p\ std} \left(\frac{\Delta_{p\ std}}{\Delta_{p\ test}} \right)^{1/2}$$

where

$C_{p\ test}$ – coefficient of S-type pitot tube

$C_{p\ std}$ – coefficient of standard pitot tube (if unknown use 0.99)

$\Delta_{p\ std}$ – velocity pressure measured by standard pitot tube, in. H_2O

$\Delta_{p\ test}$ = velocity pressure measured by S-type pitot tube, in. H_2O

6.2 Dry Gas Meter and Orifice Meter

6.2.1 Principle. The dry test and orifice meters of the particulate sampling train are calibrated using a wet test meter.

6.2.2 Apparatus. A wet test meter or equivalent capable of measuring 1 ft^3 per revolution with ±1% accuracy is required.

6.2.3 Procedure. Connect the components as shown in Figure F-1. Run the equipment with the orifice manometer set at 0.5 in. H_2O for at least 15 min to allow the pump to warm up and all interior surfaces of the wet test meter to become wetted. After the warm-up period, run tests and record the required parameters on the data sheet shown in Figure F-2.

6.2.4 Calculations

6.2.4.1 Ratio of wet to dry test meter volume. Calculate γ, the ratio of the wet test meter volume to dry test meter volume, using Equation F-2.

$$[F-2] \qquad \gamma = \frac{V_w\left(P_b + \frac{\Delta m}{13.6}\right)(t_d + 460)(1 - B_{ws})}{V_d\left(P_b + \frac{\Delta H}{13.6}\right)(t_w + 460)}$$

If the average value of γ is not within 0.99 and 1.01 (1.0 desired), the dry test meter must be adjusted internally and the calibration procedure repeated.

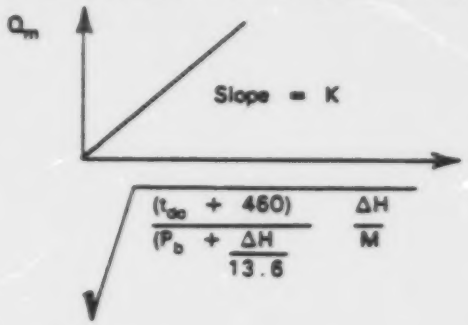
6.2.4.2 Orifice meter. Flow through an orifice meter may be determined using Equation F-3

$$[F-3] \qquad Q_m = K\sqrt{\frac{(t_{do} + 460)\,\Delta H}{\left(P_b + \frac{\Delta H}{13.6}\right)M}}$$

Note also that Q_m may be obtained from the flow rate through the wet test meter using Equation F-4.

$$[F-4] \qquad Q_m = \frac{V_w}{\theta}\,(1-B_{wo})\,\frac{(t_{do} + 460)}{(t_w + 460)}\,\frac{\left(P_b + \frac{\Delta m}{13.6}\right)}{\left(P_b + \frac{\Delta H}{13.6}\right)}$$

The proportionality constant K in Equation F-3 is specific for the orifice meter being calibrated and is determined by varying the flow rate over the working range of the orifice meter and plotting the results in a manner similar to Scheme F-1. Use Equation F-4 to determine Q_m.



SCHEME F-1 ORIFICE CALIBRATION

Most commercially available stack sampling trains utilize a nomograph to assist in adjusting the sampling rate. One of the requirements for the operation of this nomograph is to establish a value for the parameter $\Delta H@$. $\Delta H@$ is defined as the pressure drop across the orifice to give a flow rate of 0.75 ft³/min at 70 °F, 29.92 in. Hg, and a molecular weight of dry air of 28.95 lb/lb-mole. Equation F-3 may be rearranged and solved for $\Delta H@$ using the above conditions to yield Equation F-5. By substituting the constant K as determined previously, the parameter $\Delta H@$, specific for the orifice meter being calibrated, is determined.

$$[F-5] \qquad \Delta H@ = \frac{0.919}{K^2}$$

where

γ - ratio of wet test meter volume to dry test meter volume

Q_m - flow rate through orifice meter, ft³/min

$\Delta H@$ - pressure drop across the orifice meter required to give flow rate of 0.75 ft³/min at 70 °F and 29.92 in. Hg, in. H_2O

t_d - average dry test meter temperature, °F

t_{di} - dry test meter inlet temperature, °F

t_{do} - dry test meter outlet temperature, °F

Δm - wet test meter manometer reading, in. H_2O

M - molecular weight of dry air, 28.95 lb/lb-mole

K - proportionality constant,

$$\frac{ft^3}{min}\left(\frac{\text{in. Hg}}{°R\ \text{in. } H_2O}\ \frac{lb}{lb\text{-mole}}\right)^{1/2}$$

V_w - wet test meter volume, ft^3

V_d - dry test meter volume, ft^3

P_b - absolute barometric pressure, in. Hg

ΔH - pressure drop across the orifice meter, in. H_2O

13.6 - conversion factor, in. H_2O/in. Hg

t_w - wet test meter temperature, °F

460 - conversion factor, °F to °R

θ - time, min

0.919 - constant, (ft^6/min^2) (in. Hg/°R) (lb/lb-mole)

B_w - proportion by volume of water vapour passing through the wet test meter calculated from partial pressure data published in chemistry, physics, and engineering handbooks

NOTE - average dry test meter temperature is calculated from the equation

$$t_d = \frac{t_{di} + t_{do}}{2}$$

6.3 Rotameter

6.3.1 Principle. The rotameter may be calibrated using any primary flow measuring device such as a volumetric gasometer or bubble tower. However, in lieu of such a device, the following procedure using a previously calibrated wet test meter may be used. The apparatus is arranged as shown in Figure F-3.

6.3.2 Apparatus

6.3.2.1 Wet test meter. A wet test meter with water manometer on the inlet is needed.

6.3.2.2 Miscellaneous. Barometer, thermometer, stopwatch, air supply, and flow control valve are required.

6.3.3 Procedure. Connect the apparatus as shown in Figure F-3. Appreciable pressure drop can be avoided by making the connections as short as possible and keeping the inside diameter of all tubing as large as possible. Adjust the flow through the rotameter to the desired rate, and record the time and wet test meter total volume for evenly spaced points on the rotameter scale going from low values to high. Repeat the test going from high to low. Note wet test meter manometer reading, water temperature, and other required data for each rotameter setting according to Figure F-4.

6.3.4 Calculations

6.3.4.1 Rotameter flow rates. Calculate the indicated flow rates for each rotameter reading by dividing the wet test meter volume change by the elapsed time. Convert the indicated flow rates to reference conditions, 77 °F and 29.92 in. Hg, using Equation F-6.

$$[F\text{-}6] \qquad Q_{ref} = Q(P_w - P_v)\ \frac{t_a + 460}{P_w(t_w + 460)}\ \left(\frac{t_a + 460}{T_{ref}}\right)^{1/2}$$

where

Q_{ref} – rotameter flow rate at reference conditions, ft^3/min

Q – flow rate indicated by wet test meter, ft^3/min

T_{ref} – reference temperature, 537 °R

t_w – wet test meter temperature (water temperature of wet test meter), °F

t_a – room temperature, °F

P_w – gas pressure during calibration at the wet test meter inlet, in. Hg

P_v – partial pressure of water vapour in air at wet test meter temperature, in. Hg

P_b – barometric pressure, in. Hg

13.6 – conversion factor, in. H_2O/in. Hg

Δm – wet test meter manometer reading, in. H_2O

NOTE

$$P_w = P_b + \frac{\Delta m}{13.6}$$

6.3.4.2 Calibration curves. Prepare the calibration curve using all points and label "at 77 °F and 29.92 in. Hg". Subsequent use of the rotameter involves taking the indicated flow off the curve and correcting it to reference conditions using Equation F-7.

$$[F-7] \qquad Q_{std} = \frac{Q_i(T_{std})}{t_s + 460} \frac{P_r}{P_{std}} \left(\frac{T_{std}}{t_s + 460}\right)^{1/2}$$

where

Q_i – indicated flow rate from calibration curve, ft^3/min

P_r – rotameter pressure, in. Hg

P_{std} – reference pressure, 29.92 in. Hg

NOTE – In most instances, P_r may be assumed to be barometric pressure, P_b in. Hg

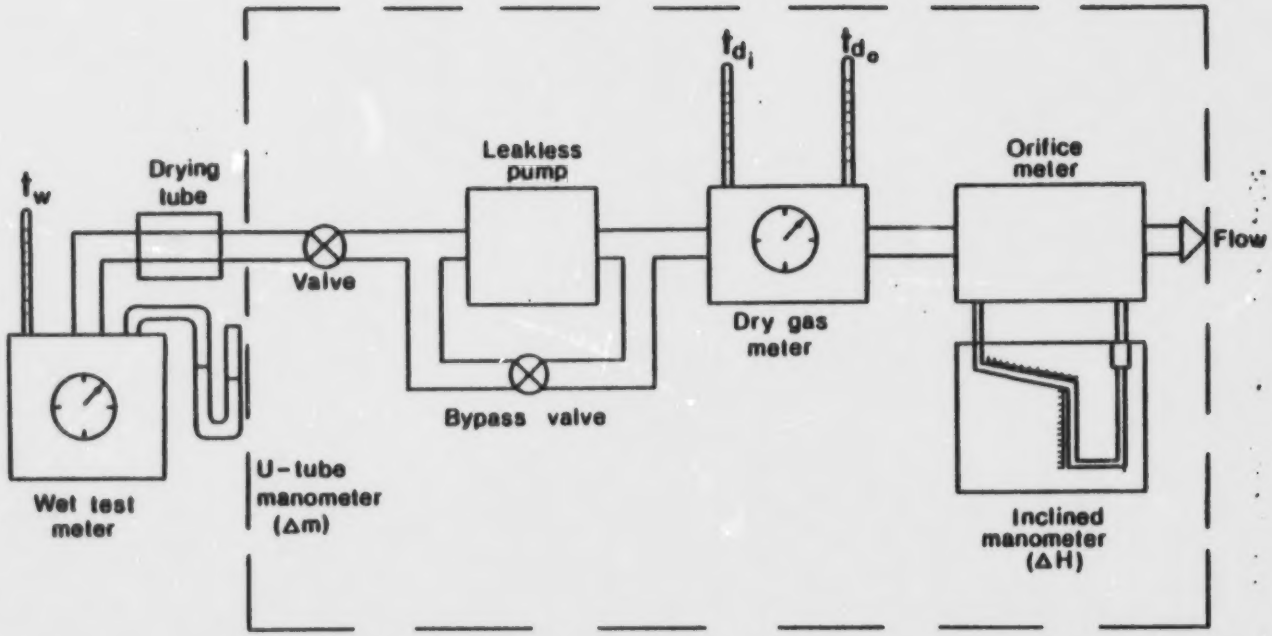


FIGURE F-1 ASSEMBLY FOR CALIBRATION OF DRY GAS METER AND ORIFICE METER

FIGURE F-2 DRY GAS METER AND ORIFICE METER CALIBRATION AND CALCULATION DATA SHEET

Date _____

Barometric pressure, P_b, in. Hg _____

Dry Gas meter No. _____

Orifice manometer setting ΔH, in. H_2O	Gas volume wet gas meter V_w, ft^3	Gas volume dry gas meter V_d, ft^3	Temperature °F				Time θ, min	Wet test meter manometer reading Δ m, in. H_2O
			Wet test meter t_w	Dry gas meter				
				Inlet t_{di}	Outlet t_{do}	Average t_d		
0.5	5							
1.0	5							
2.0	10							
4.0	10							
6.0	10							
8.0	10							

Calculations

Y	Q_w	Q_w/K	K
$\frac{V_w\left(P_b + \frac{\Delta m}{13.6}\right)}{V_d\left(P_b + \frac{\Delta H}{13.6}\right)} \quad \frac{(t_d + 460)}{(t_w + 460)} \quad (1 - B_{ws})$	$Y \frac{V_d}{\theta} \quad \frac{t_{do} + 460}{t_d + 460}$	$\sqrt{\frac{(t_{do} + 460)\ \Delta H}{\left(P_b + \frac{\Delta H}{13.6}\right) 28.95}}$	

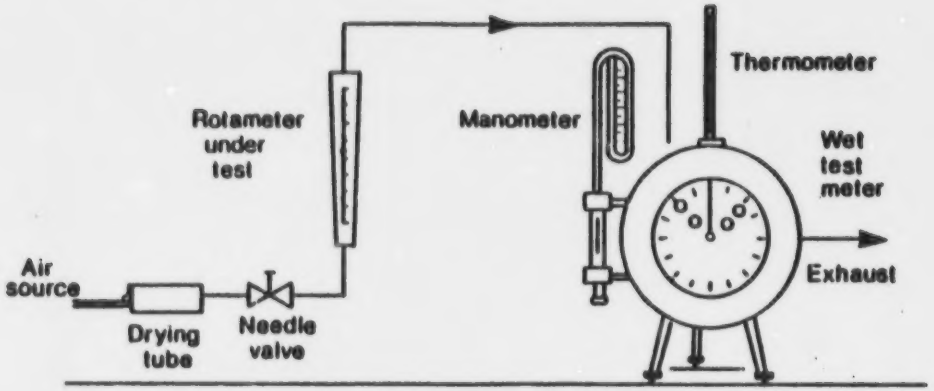


FIGURE F-3 CALIBRATION ASSEMBLY USING WET TEST METER

FIGURE F-4 ROTAMETER CALIBRATION DATA SHEET

Rotameter setting	Wet test meter temp. t_w (°F)	Room temp. t_r (°F)	Manometer reading Δm (in. H_2O)	Gas vol. wet test meter V_w (ft^3)	Time θ (min)	Indicated flow, $Q = V_w/\theta$ (ft^3/min)	Corrected flow Q_{std} (ft^3/min)

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APPENDIX B

PRODUCER GAS ANALYSIS

PRODUCER GAS ANALYSIS

This procedure describes the analysis of clean, dry producer gas for its constituent gases: hydrogen, methane, carbon dioxide, ethylene, ethane, oxygen, nitrogen and carbon monoxide. The minimum concentration of each gas which is detected with reliable precision is 0.1% by volume.

APPARATUS

A Hewlett Packard 5700A gas chromatograph, equipped with a thermal conductivity detector and a 1 cm^3 sample valve is used for the analysis. The instrument is connected to a 5880A GC terminal, level four. A 6 port and 10 port automatic valve switching system is used for sample injection, column isolation and backflushing.

COLUMNS

Two columns are used in series:

6' x 1/8" Porapak Q, 80-100 mesh and
10' x 1/8" Molecular sieve 13X, 60-80 mesh.

SAMPLE INJECTION

Plastic film sampling bags are connected to the sampling valve by a short length of Tygon tubing. About 10 cm^3 of sample is used to flush the loop immediately before starting the analysis.

CALIBRATION

Three calibration gas mixtures are used to achieve a multi-level calibration. Each gas is injected twice and the averages of the duplicate injections used to establish the calibration values. The compositions of the gas mixtures bracket the expected concentrations of the samples.

A calibration curve for hydrogen is prepared by successive dilution of hydrogen in argon.

ANALYSIS FOR GASES OTHER THAN HYDROGEN

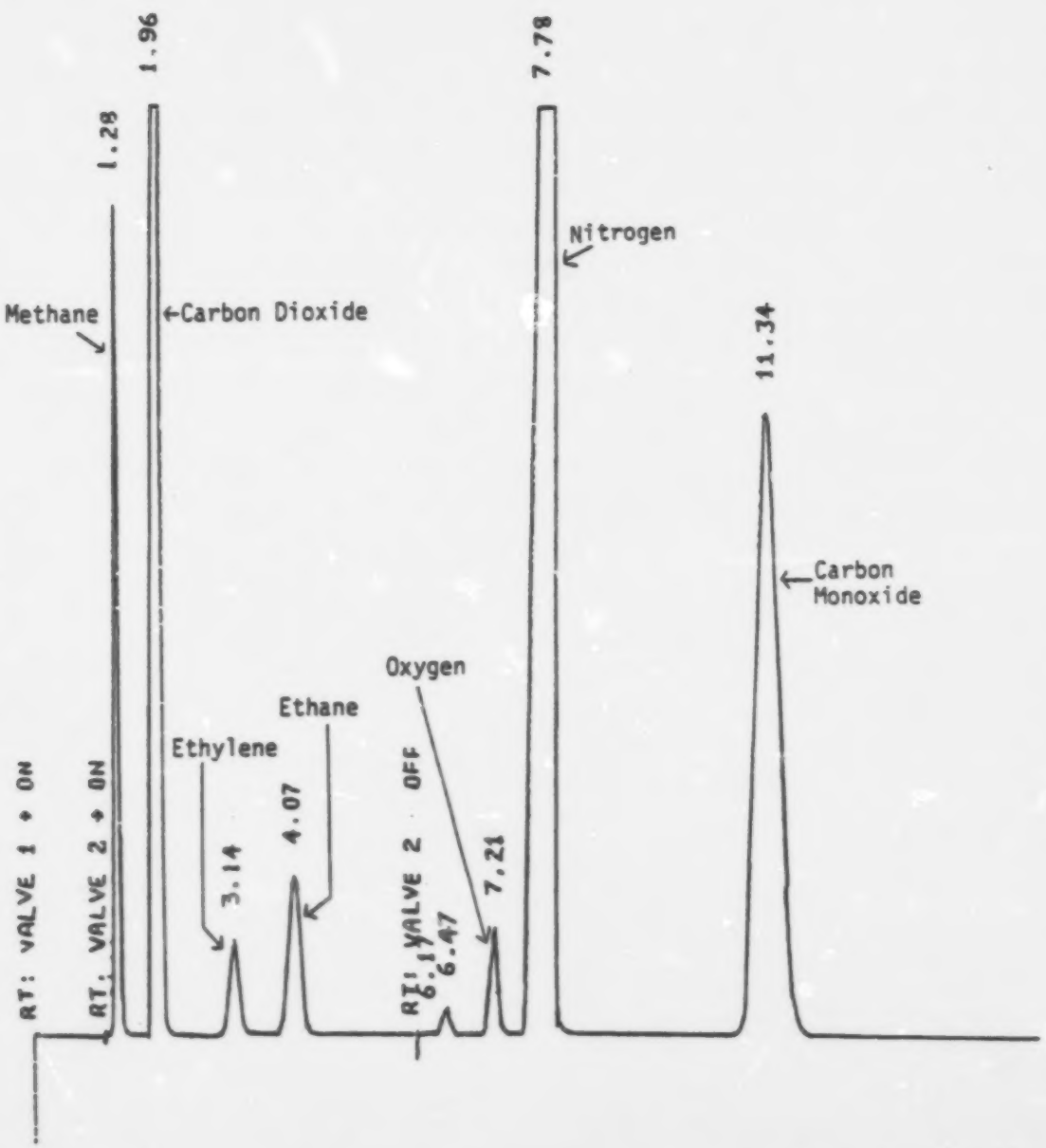
Methane, carbon dioxide, ethylene, ethane, carbon monoxide, nitrogen and oxygen are analyzed using both columns with helium as the carrier gas. The first four gases are separated on the Porapak column, the latter three gases on the molecular sieve column. The buildup of heavy hydrocarbons on the Porapak column is eliminated by backflushing the column before separation of the gases on the molecular sieve column. A typical chromatogram is shown in Figure B-1.

Instrument conditions:

sample volume 1 cm^3
helium flow rate 25 cc/min
injection temperature 100°C
detector temperature 150°C
oven temperature 60°C
detector current 150 ma
polarity B
threshold 4
peak width 0.04
attenuation 2^6
signal C.

FIGURE B-1

Gas Chromatogram of Producer Gas



The run table for valve switching was set up as follows:

Run Time (RT)	0.01	Valve 1 ON
RT	1.19	Valve 2 ON
RT	6.20	Valve 1 OFF
RT	11.40	Valve 2 OFF
RT	15.00	Stop.

The run table shows that, at 0.01 minutes after injection, valve 1 was opened, allowing the sample to flow through both columns. At 1.19 minutes valve 2 was closed, trapping carbon monoxide, oxygen and nitrogen at the start of the molecular sieve column. From 1.19 to 6.20 minutes, methane, carbon dioxide, ethylene and ethane were eluted from the Porapak column. At 6.20 minutes valve 1 was closed and the Porapak column backflushed for 5.20 minutes. At 11.40 minutes, valve 2 was opened and oxygen, nitrogen and carbon monoxide were eluted from the molecular sieve column.

ANALYSIS FOR HYDROGEN

The molecular sieve column is used to separate hydrogen from nitrogen, using argon as the carrier gas. Carbon dioxide is prevented from deactivating the molecular sieve column by closing valve 2 before carbon dioxide can enter the column.

Instrument conditions:

sample volume 1 cm^3
argon flow rate 20 cm^3/min
injection temperature 100°C
detector temperature 150°C
oven temperature 60°C
detector current 150 ma
polarity A
threshold 4

peak width .04
attenuation 2^8
signal C.

The run table for valve switching was set up as follows:

Run Time (RT)	0.01	Valve 1 ON
RT	1.65	Valve 2 ON
RT	5.0	Valve 2 OFF
RT	6.5	Stop.

ANALYSIS FOR PROPANE AND HIGHER HYDROCARBONS

Analysis of producer gas for propane and higher hydrocarbons is carried out, if required, using the Porapak column and an oven temperature of about 100°C. All other conditions are as described for the analysis of gases other than hydrogen.

APPENDIX C

GAS CHROMATOGRAPHIC ALCOHOL ANALYSIS

NATIONAL COUNCIL FOR AIR AND STREAM IMPROVEMENT
Technical Bulletin #310 - April 1978

Gas Chromatographic Alcohol Analysis Procedure Used In the Kraft Pulping Process Condensate Study

Method:

Direct injection of condensate sample on a gas chromatographic column for determination of the concentration of alcoholic constituents.

Laboratory Equipment and Materials:

Gas chromatograph equipped with FID, temperature programming and dual column capability
Related chromatographic supplies
Appropriate glassware
Prepurified hydrogen, helium, and medical grade air
Redistilled methanol (standard)
Absolute or 95% ethanol (standard)

Procedure:

1. Prepare dual 0.2 mm I.D. x 1 m 6% FFAP on Porapak T (100-120 mesh) (column packing obtained from Analab) Preferably of pyrex glass construction
2. Condition the columns overnight at 170°C reached by temperature programming from ambient at 4°C per minute
3. Prepare methanol and ethanol (CH_3OH, F.W. = 32.04; C_2H_5OH, F.W. = 46.07) standards at appropriate concentrations (generally 1-2000 ppm). This was performed by adding 1 ml of the pure standard solution, by pipette, into a 1 liter volumetric flask partially filled with water and then bringing the total volume to 1 liter. The concentrations of the solutions were then determined by calculations (sp. gr. $CH_3OH = 0.792\ ^{20}_{4}$, sp. gr. absolute $C_2H_5OH = 0.789\ ^{20}_{4}$). This would be equivalent to standard methanol and ethanol stock solutions of 792 mg/l and 789 mg/l respectively, at 20°C. The pipette is held below the surface of the water solution when introducing the pure alcohol to prevent evaporation. Subsequent concentrations are obtained by dilution of these stock solutions.
4. The gas chromatograph operational parameters were set as follows:
   - He (carrier) at 20 ml/min
   - H_2 at 20 ml/min
   - Air at 300 ml/min
   - Injector and detector temperatures at 160°C
   - Temperature program from 80°C for 5 minutes to 140°C at 4°C per minute
5. Inject the standards (at least 3 concentrations in duplicate) of the proper concentration to establish the calibration curves, plotting concentration vs. response.
6. Inject appropriate quantities of sample (such that the quantity of alcohol present can be adequately determined, yet such that the flame in the detector is not extinguished by too much water) and determine the alcohol concentration from the curves previously generated. Note: CH_3OH elutes in approximately 10 minutes, C_2H_5OH in approximately 16.5 minutes. Other peaks from condensate samples have been observed at about 13, 14.5, and 18 minutes.

Additional Information:

Repeated use of the column allowed buildup of terpenes and other materials, eventually inducing column bleed. This can be minimized by running the columns at high temperatures (about 170°C) overnight, driving these terpenes and other compounds off the column.

The carrier gas was helium rather than nitrogen to minimize the amount of oxygen present. Oxygen at high temperatures in this column will produce acetaldehyde which subsequently condenses and absorbs on the column when trace quantities of amines are present.

The 6% FFAP column coating is a Carbowax 20M treated with 2-nitroterephthalic acid. The Porapak T column support demonstrates the highest polarity and therefore the greatest water retention in the Porapak series of column supports.

Method Precision and Accuracy:

To determine the precision and accuracy of this method in determining alcohol concentrations, two methanol standards of 792 mg/l were prepared (A,B). These solutions were sequentially diluted to yield, in addition to the original 792 mg/l, solutions of 79.2 and 7.92 mg/l (A1, A2, A3 and B1, B2, B3 successively). Finally two vials, designated a and b, from each solution were taken for two 2 µl injections each by an automatic injector. Therefore the identification symbol for each container or vial would be A1a, A1b, A2a, A2b, A3a, A3b, B1a, B1b, B2a, B2b, B3a, and B3b. Thus A2b would indicate from standard solution A at 79.2 mg/l, the second vial.

Results:

The results of these investigations, as presented in Table I indicated that no group of averaged samples had an average percent deviation greater than 2 percent, in fact the largest single point deviation was only 3.57 percent. The final column, the average data from all vials, indicates that when preparing duplicate standards and comparing the results of 4 injections each, the average percent deviation was 1.6 percent. On a two injection each basis, the maximum average percent deviation between two standards was 3.25 percent. Finally, the maximum deviation of any two points was less than 7.0 percent.

Various other methods of determining peak area were evaluated including the integrator readout, the calculated area utilizing either a flat or trapezoidal baseline (measured by triangulation, $A = \frac{1}{2}\, bh$), and the peak height again utilizing either a flat or trapezoidal baseline. The results of these measurements are presented in Table II.

Table II. Comparison of Peak Area/Height Measurements by Various Methods

Concentration mg/l	Method	$\bar{x}$[1]	s.d.[2]	Percent[3] s.d.
7.9	Calc. area (flat b.l.[4])	42.91	5.37	12.53
	Calc. area (trap b.l.[5])	25.68	2.01	8.12
	Height (flat b.l.[4])	0.738	0.029	3.90
	Height (trap b.l.[5])	0.546	0.016	2.93
	Integrated Area	4458	110.6	2.48
79.2	Calc. area (flat b.l.[4])	268.1	15.75	5.87
	Height (flat b.l.[4])	4.96	0.171	3.46
	Integrated area	31489	568	1.80
792	Calc. area (flat b.l.[4])	2577	137.5	5.34
	Height (flat b.l.[4])	51.15	2.070	4.05
	Integrated area	314936	7633	2.42

1. $\bar{x}$ denotes average
2. s.d. denotes standard deviation
3. Percent s.d. denotes percent standard deviation
4. Flat b.l. denotes flat baseline
5. Trap b.l. denotes trapezoidal baseline

The data in the table indicates that throughout the range investigated, the integrator area determination yielded results with the most precision while the peak height, utilizing a trapezoidal baseline when necessary, also yielded consistent results.

Figures 1, 2 and 3 further delineate this data for calculated peak area, measured peak height, and integrator peak area respectively vs. concentration. These graphs indicate that the peak height determination method is the most accurate in determining concentration as the curve developed (Figure 2) most closely passes through the origin. The calculated peak area determination is second and the integrator area is also close to passing through (0,0). It appears as if there may be some difficulty in separating the water and methanol peaks when using the integrator and determining methanol concentrations of about 10 mg/l or less.

Finally, two ethanol peaks were analyzed for peak area by manual means and compared to ethanol peaks injected both before and after the ethanol injection. A comparison of the two compounds' peak area indicated that on a mass basis the detector response factor of ethanol when compared to methanol was 1.47 whereas on a molar basis the factor was 1.02.

In summary, these results indicate that the use of these chromatographic techniques, utilizing a 0.02 mm I.D. x 1 m 6% FFAP on Porapak T (100-120 mesh) column is more than adequate for analyzing condensate samples from the multiple-effect evaporators. Above 10 mg/l methanol concentrations the errors in the analysis were less than 10 percent when comparing two values if the values are the average of two injections by an automatic injector.

APPENDIX D

ANALYSIS OF CONDENSATE BY LIQUID CHROMATOGRAPHY

ANALYSIS OF CONDENSATE BY LIQUID CHROMATOGRAPHY

This procedure describes the analysis of condensate for formaldehyde, acetic acid and propionic acid. There are a number of other procedures which would achieve the same results.

PROCEDURE

A Hewlett Packard 1048A High Performance Liquid Chromatograph with a refractive index detector was used for the analysis. The eluent was deionized water adjusted to pH 3.5 with sulfuric acid, at a flow rate of 1.5 mL/min. A 20 cm by 4.6 mm, 5 μm RP-8 column was used at an oven temperature of 40°C.

The samples were filtered through a 1 μm glassfibre filter before injection of 20 μl onto the column.

Standards were prepared from reagent grade chemicals dissolved in acidified deionized water, at concentrations from 2 to 10 mg/mL. Reagent grade formaldehyde solution was standardized by a sodium sulfite procedure (1).

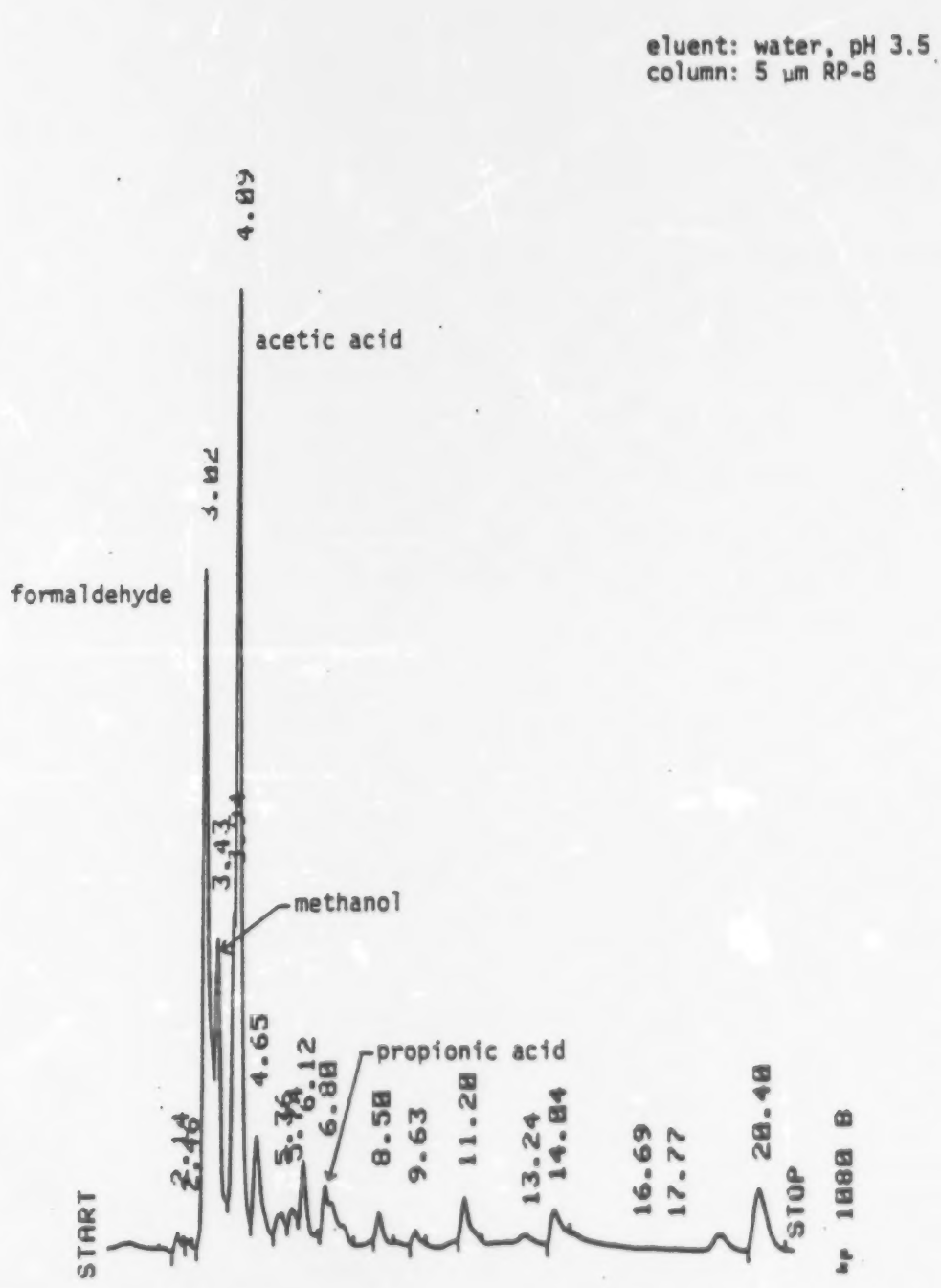
DISCUSSION

Formaldehyde, acetic acid and propionic acid are quantified in the condensate. Figure D-1 shows a typical chromatogram.

Propionic acid is poorly resolved from an unknown peak, but the resolution can be improved by using two columns in series. Formic acid and glycolic acids are not separated by this procedure and their retention time is close to that of formaldehyde. An ion exchange column may be used to separate formic and glycolic acids.

(1) Walker, J.F. 1964. Formaldehyde. American Chemical Society, Monograph Series, Third Edition, Reinhold Publishing Company. p. 486.

FIGURE D-1
LIQUID CHROMATOGRAM OF CONDENSATE



APPENDIX E

WORKSHEETS FOR STACK SAMPLING CALCULATIONS

STACK SAMPLING CALCULATIONS

A. Stack Gas Moisture Content

1. $(V_w)_{ref} = (V_{lc})(\frac{\rho H_2O}{MH_2O})(\frac{T_{ref}}{P_{ref}})(R)$

$= (0.0464)\ V_{lc}$

$= (0.0464)(\quad)$

$= \_\_\_\_\_\ ft^3$ at 15°C and 1 atm.

2. $(V_m)_{ref} = (V_m)(\frac{T_{ref}}{T_m})(\frac{P_{bar} + \Delta H/13.6}{P_{ref}})$

$= (17.35)(\frac{V_m}{T_m})(P_{bar} + \Delta H/13.6)$

$= (17.35)(\_\_\_\_\_)(\quad + \frac{\_\_\_\_\_}{13.6})$

$= \_\_\_\_\_\ ft^3$ at 15°C and 1 atm.

3. $B_{wo} = [\frac{V_{w\ ref}}{V_{w\ ref} + V_{m\ ref}}]$

$= [\frac{\_\_\_\_\_}{+}]$

$= \_\_\_\_\_$.

B. Stack Gas Composition

1. Dry molecular weight of gas:

M_d = $0.02(\%H_2) + 0.32(\%O_2) + 0.28(\%N_2) + 0.16(\%CH_4) +$
$0.30(\%C_2H_6) + 0.28(\%C_2H_4) + 0.44(\%CO_2) + 0.28(\%CO)$

= $0.02(\_\_\_\_\_) + 0.32(\_\_\_\_\_) + 0.28(\_\_\_\_\_) + 0.16(\_\_\_\_\_) +$
$0.30(\_\_\_\_\_) + 0.28(\_\_\_\_\_) + 0.44(\_\_\_\_\_) + 0.28(\_\_\_\_\_)$

= _____ + _____ + _____ + _____ +
_____ + _____ + _____ + _____

= _____ lb/lb-mole

2. Wet molecular weight of gas:

M_s = $(M_d)(1-B_{wo}) + 18\ B_{wo}$

= (_____)(1-_____) + 18 (_____)

= _____ lb/lb-mole

C. Stack Gas Velocity and Flow Rate

1. Average velocity:

$$(V_s)_{avg} = (K_p)(C_p)(\sqrt{\Delta P})_{avg}\sqrt{\frac{(T_s)_{avg}}{P_s M_s}}$$

$$= 85.49\ (\_\_\_\_\_)\ \sqrt{\_\_\_\_}\ \sqrt{\frac{\_\_\_\_}{x}}$$

$$= \_\_\_\_\_ \text{ fps}$$

2. Actual volume:

$$Q = (3600)(V_{s\ avg})(A_s)$$

$$= (3600)(\_\_\_\_\_)(\_\_\_\_\_)$$

$$= \_\_\_\_\_ \text{ acfh at 15°C and 1 atm.}$$

3. Standard volume:

$$Q_s = (3600)(1-B_{wo})(V_{s\ avg})(A_s)\left(\frac{T_{ref}}{T_{s\ avg}}\right)\left(\frac{P_s}{P_{ref}}\right)$$

$$= (3600)(1-\_\_\_\_\_)(\_\_\_\_\_)(\_\_\_\_\_)\left(\frac{519}{\_\_\_\_\_}\right)\left(\frac{\_\_\_\_\_}{29.92}\right)$$

$$= \_\_\_\_\_ \text{ scfh at 15 °C and 1 atm.}$$

D. Concentration of Particulate Matter

$$C_s = \frac{(M)(0.01543)}{V_{m\ ref}}$$

$$= \frac{(\_\_\_\_\_)(0.01543)}{(\quad)}$$

$$= \_\_\_\_\_ \text{ grains/scf}$$

E. Emission Rate of Particulate Matter

$$ER = \frac{(Q_s)(C_s)}{7{,}000}$$

$$= \frac{(\quad\quad)(\quad\quad)}{7000}$$

$$= \quad\quad \text{lb/hr.}$$

F. Percent Isokinetic

$$I = \frac{(T_s)(V_{m\ ref})(P_{ref})(100)}{(T_{ref})(V_{s\ avg})(T)(A_n)(P_s)(60)(1-B_{wo})}$$

$$= \frac{(0.0961)(T_s)(V_{m\ ref})}{(V_{s\ avg})(T)(A_n)(P_s)(1-B_{wo})}$$

$$= \frac{(0.0961)(\quad\quad)(\quad\quad)}{(\quad\quad)(\quad\quad)(\quad\quad)(\quad\quad)(1-\quad\quad)}$$

$$= \quad\quad \%$$

APPENDIX F

WORKSHEETS FOR MASS BALANCE CALCULATIONS

MASS BALANCE CALCULATIONS

SYMBOL	DEFINITION AND UNITS	VALUE

FLOWS

A_{dry}	= Mass flow rate of dry air, kg/hr	_____
CH_{dry}	= Mass flow rate of dry char, kg/hr	_____
CH_{wet}	= Mass flow rate of wet char, kg/nr	_____
FA_{dry}	= Mass flow rate of dry fly asn, kg/hr	_____
FA_{wet}	= Mass flow rate of wet fly ash, kg/hr	_____
F_{dry}	= Mass flow rate of dry feed, kg/hr	_____
F_{wet}	= Mass flow rate of wet feed, kg/hr	_____
G_{dry}	= Volume flow rate of dry gas, m^3/hr	_____
$OV_{in}(n)$	= overall mass input for stream "n"	
$OV_{out}(n)$	= overall mass output for stream "n"	
$\sum_{in}$	= summation of input to gasifier	
$\sum_{out}$	= summation of output from gasifier	

MASS FRACTIONS

CCH	= Mass fraction of C in char	_____
CF	= Mass fraction of C in feed	_____
CFA	= Mass fraction of C in fly ash	_____
CP	= Mass fraction of C in particulates	_____
CT	= Mass fraction of C in tars	_____
CWSO	= Mass fraction of C in water sol. org.	_____
HCH	= Mass fraction of H_2 in cnar	_____
HF	= Mass fraction of H_2 in feed	_____
HFA	= Mass fraction of H_2 in fly asn	_____
HP	= Mass fraction of H_2 in particulates	_____
HT	= Mass fraction of H_2 in tar	_____
HWSO	= Mass fraction of H_2 in water sol. org.	_____
NCH	= Mass fraction of N_2 in char	_____
NF	= Mass fraction of N_2 in dry feed	_____
NFA	= Mass fraction of N_2 in fly ash	_____
NP	= Mass fraction of N_2 in particulates	_____
NT	= Mass fraction of N_2 in tar	_____

SYMBOL	DEFINITION AND UNITS	VALUE

MASS FRACTIONS (continued)

NWSO	= Mass fraction of N_2 in water sol. org.	_____
OCH	= Mass fraction of O_2 in char	_____
OF	= Mass fraction of O_2 in dry feed	_____
OFA	= Mass fraction of O_2 in fly ash	_____
OP	= Mass fraction of O_2 in particulates	_____
OT	= Mass fraction of O_2 in tar	_____
OWSO	= Mass fraction of O_2 in water sol. org.	_____
H	= Mass fraction of water vapour in dry air	_____
WCH	= Mass fraction of H_2O in char	_____
WF	= Mass fraction of H_2O in wet feed	_____
WFA	= Mass fraction of H_2O in fly ash	_____
2/18	= Mass fraction of H in H_2O	
16/18	= Mass fraction of O in H_2O	
0.232	= Mass fraction of O in dry air	
0.768	= Mass fraction of N in atmospheric air	

MASS CONCENTRATIONS

CG	= Mass conc. of C in dry gas, kg/m^3	_____
HC	= Mass conc. of H_2 in dry gas, kg/m^3	_____
NG	= Mass conc. of N_2 in dry gas, kg/m^3	_____
OG	= Mass conc. of O_2 in dry gas, kg/m^3	_____
PC	= Mass conc. of particulates, kg/m^3	_____
TC	= Mass conc. of tars, kg/m^3	_____
WC	= Mass conc. of H_2O in gas, kg/m^3	_____
WSOC	= Mass conc. of water sol. org., kg/m^3	_____

OTHER

D	= Density of dry gas (mass conc.), kg/m^3	_____
PCCL	= percent closure	

Calculation of Dry Air Input, A_{dry}

1. Using the dry bulb and wet bulb temperatures of the ambient air taken during the test and a psycnrometric chart, determine tne concentration of moisture in the air,

$$\frac{(\quad)\text{grains } H_2O}{\text{lb of dry air}}$$

2. Calculate the mass fraction of moisture in the air

$$H = \frac{(\quad \text{gr } H_2O/\text{lb dry air})}{7000 \text{ gr/lb}} = \_\_\_\_\_$$

3. Calculate the dry air flow rate from the measured air input rate

$$A_{dry} = (A_{wet})(1-H)(0.075)(0.4545)\frac{288}{T}$$

$$A_{dry} = (\quad)(1-\quad)(0.075)(0.4545)\frac{288}{T} = \_\_\_\_\_ \text{ kg/hr}$$

where:

A_{dry} = dry air input flowrate, kg/nr

A_{wet} = measured input flowrate, ft^3/hr

H = mass fraction of moisture in air, lb H_2O/lb dry air

0.075 = density of dry air, lb/ft^3

0.4545 = conversion factor, lb to kg

$\frac{288}{T}$ = temperature correction factor, input air to 15°C, (288 °K)

T = air temperature in °K

MASS BALANCE, IN:

1. Dry Feed

$OV_{in}(1)$ = F_{dry}

= _____ kg/hr

2. Moisture in Feed

$OV_{in}(2)$ = $(F_{wet})(WF)$

= (_____ kg/hr)(_____)

= _____ kg/hr

3. Dry Air

$OV_{in}(3)$ = A_{dry}

= _____ kg/hr

4. Moisture in Air

$OV_{in}(4)$ = $(A_{dry})(H)$

= (_____ kg/hr)(_____)

= _____ kg/hr

MASS BALANCE, OUT:

1. Dry Gas

$OV_{out}(1)$ = $(G_{dry})(D)$

= (_____ m^3/hr)(_____ kg/m^3)

= _____kg/hr

2. Particulates

$OV_{out}(2)$ = $(G_{dry})(PC)$

= (_____ m^3/hr)(_____ kg/m^3)

= _____ kg/hr

3. Tars

$OV_{out}(3)$ = $(G_{dry})(TC)$

= (_____ m^3/hr)(_____ kg/m^3)

= _____ kg/hr

4. Water Soluble Organics

$OV_{out}(4)$ = $(G_{dry})(WSOC)$

= (_____ m^3/hr)(_____ kg/m^3)

= _____ kg/hr

5. Moisture in Gas

$OV_{out}(5)$ = $(G_{dry})(WC)$

= (_____ m^3/hr)(_____ kg/m^3)

= _____ kg/hr

6. Char

$OV_{out}(6)$ = CH_{dry}

= _____ kg/hr

7. Moisture in Char

$OV_{out}(7)$ = $(CH_{wet})(WCH)$

= (_____ kg/hr)(_____)

= _____ kg/hr

8. Fly Ash

$OV_{out}(8)$ = FA_{dry}

= _____ kg/hr

9. Moisture in Fly Ash

$OV_{out}(9)$ = $(FA_{wet})(WFA)$

= (_____ kg/hr)(_____)

= _____ kg/hr

MASS BALANCE, CARBON

IN:

1. Dry Feed

$C_{in}(1)$ = $(F_{dry})(CF)$

= (_____)(_____)

= _____ kg/hr

OUT:

1. Dry Gas

$C_{out}(1)$ = $(G_{dry})(CG)$

= (_____)(_____)

= _____ kg/hr

2. Particulates

$C_{out}(2)$ = $(G_{dry})(PC)(CP)$

= (_____)(_____)(_____)

= _____ kg/hr

3. Tars

$C_{out}(3)$ = $(G_{dry})(TC)(CT)$

= (_____)(_____)(_____)

= _____ kg/hr

4. Water Soluble Organics

$C_{out}(4)$ = $(G_{dry})(WSOC)(CWSO)$

= (_____)(_____)(_____)

= _____ kg/hr

5. Moisture in Gas

$C_{out}(5)$ = Negligible

6. Char

$C_{out}(6)$ = $(CH_{dry})(CCH)$

= (_____)(_____)

= _____ kg/hr

7. Fly Ash

$C_{out}(7)$ = $(FA_{dry})(CFA)$

= (_____)(_____)

= _____ kg/hr

MASS BALANCE, HYDROGEN

IN:

1. Dry Feed

$H_{in}(1) = (F_{dry})(HF)$

$= (\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

2. Moisture in Feed

$H_{in}(2) = (F_{wet})(WF)(\frac{2}{18})$

$= (\_\_\_\_\_)(\_\_\_\_\_)(\frac{2}{18})$

$= \_\_\_\_\_$ kg/hr

3. Dry Air

$H_{in}(3)$ = Negligible

4. Moisture in Air

$H_{in}(4) = (A_{dry})(H)(\frac{2}{18})$

$= (\_\_\_\_\_)(\_\_\_\_\_)(\frac{2}{18})$

$= \_\_\_\_\_$ kg/hr

OUT:

1. Dry Gas

$H_{out}(1) = (G_{dry})(HC)$

$= (\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

2. Particulates

$H_{out}(2) = (G_{dry})(PC)(HP)$

$= (\_\_\_\_)(\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

3. Tars

$H_{out}(3) = (G_{dry})(TC)(HT)$

$= (\_\_\_\_)(\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

4. Water Soluble Organics

$H_{out}(4) = (G_{dry})(WSOC)(HWSO)$

$= (\_\_\_\_)(\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

5. Moisture in Gas

$H_{out}(5) = (G_{dry})(WC)(\frac{2}{18})$

$= (\_\_\_\_)(\_\_\_\_\_)(\frac{2}{18})$

$= \_\_\_\_\_$ kg/hr

6. Char

$H_{out}(6) = (CH_{dry})(HCH)$

$= (\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

7. Moisture in Char

$H_{out}(7) = (CH_{wet})(WCH)(\frac{2}{18})$

$= (\_\_\_\_\_)(\_\_\_\_\_)(\frac{2}{18})$

$= \_\_\_\_\_$ kg/hr

8. Fly Ash

$H_{out}(8) = (FA_{dry})(HFA)$

$= (\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

9. Moisture in Fly Ash

$H_{out}(9) = (FA_{wet})(WFA)(\frac{2}{18})$

$= (\_\_\_\_\_)(\_\_\_\_\_)(\frac{2}{18})$

$= \_\_\_\_\_$ kg/hr

MASS BALANCE, OXYGEN

IN:

1. Dry Feed

$O_{in}(1) = (F_{dry})(OF)$

$= (\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

2. Moisture in Feed

$O_{in}(2) = (F_{wet})(WF)(\frac{16}{18})$

$= (\_\_\_\_\_)(\_\_\_\_\_)(\frac{16}{18})$

$= \_\_\_\_\_$ kg/hr

3. Dry Air

$O_{in}(3) = (A_{dry})(0.232)$

$= (\_\_\_\_\_)(0.232)$

$= \_\_\_\_\_$ kg/hr

4. Moisture in Air

$O_{in}(4) = (A_{dry})(H)(\frac{16}{18})$

$= (\_\_\_\_\_)(\_\_\_\_\_)(\frac{16}{18})$

$= \_\_\_\_\_$ kg/hr

OUT:

1. Dry Gas

$O_{out}(1) = (G_{dry})(OG)$

$= (\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

2. Particulates

$O_{out}(2) = (G_{dry})(PC)(OP)$

$= (\_\_\_\_)(\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

3. Tars

$O_{out}(3) = (G_{dry})(TC)(OT)$

$= (\_\_\_\_)(\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

4. Water Soluble Organics

$O_{out}(4) = (G_{dry})(WSOC)(OWSO)$

$= (\_\_\_\_)(\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

5. Moisture in Gas

$O_{out}(5) = (G_{dry})(WC)(\frac{16}{18})$

$= (\_\_\_\_)(\_\_\_\_\_)(\frac{16}{18})$

$= \_\_\_\_\_$ kg/hr

6. Char

$O_{out}(6) = (CH_{dry})(OCH)$

$= (\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

7. Moisture in Char

$O_{out}(7) = (CH_{wet})(WCH)(\frac{16}{18})$

$= (\_\_\_\_\_)(\_\_\_\_\_)(\frac{16}{18})$

$= \_\_\_\_\_$ kg/hr

8. Fly Ash

$O_{out}(8) = (FA_{dry})(OFA)$

$= (\_\_\_\_\_)(\_\_\_\_\_)$

$= \_\_\_\_\_$ kg/hr

9. Moisture in Fly Ash

$O_{out}(9) = (FA_{wet})(WFA)(\frac{16}{18})$

$= (\_\_\_\_\_)(\_\_\_\_\_)(\frac{16}{18})$

$= \_\_\_\_\_$ kg/hr

MASS BALANCE, NITROGEN

IN:

1. Dry Feed

$N_{in}(1)$ = $(F_{dry})(NF)$

= (_____)(_____)

= _____ kg/hr

2. Moisture in Feed

$N_{in}(2)$ = Negligible

3. Dry Air

$N_{in}(3)$ = $(A_{dry})(0.768)$

= (_____)(0.768)

= _____ kg/hr

4. Moisture in Air

$N_{in}(4)$ = Negligible

OUT:

1. Dry Gas

$N_{out}(1)$ = $(G_{dry})(NG)$

= (_____)(_____)

= _____ kg/hr

2. Particulates

$N_{out}(2)$ = $(G_{dry})(PC)(NP)$

= (_____)(_____)(_____)

= _____ kg/hr

3. Tars

$N_{out}(3)$ = $(G_{dry})(TC)(NT)$

= (_____)(_____)(_____)

= _____ kg/hr

4. Water Soluble Organics

$N_{out}(4)$ = $(G_{dry})(WSOC)(MWSO)$

= (____)(_____)(_____)

= _____ kg/hr

5. Moisture in Gas

$N_{out}(5)$ = Negligible

6. Char

$N_{out}(6)$ = $(CH_{dry})(NCH)$

= (_____)(_____)

= _____ kg/hr

7. Moisture in Char

$N_{out}(7)$ = Negligible

8. Fly Ash

$N_{out}(8)$ = $(FA_{dry})(NFA)$

= (_____)(_____)

= _____ kg/hr

9. Moisture in Fly Ash

$N_{out}(9)$ = Negligible

MASS BALANCE - TOTALS

1. OVERALL

$\Sigma_{in} = \sum_{i=1}^{n}$ $\Sigma_{out} = \sum_{i=1}^{n}$

Σ in = _____+_____+_____+_____ = _____kg/hr

Σ out = _____+_____+_____+_____+_____+_____
+_____+_____+_____+_____ = _____kg/hr

2. CARBON

Σ in = _____+_____+_____+_____ = _____kg/hr

Σ out = _____+_____+_____+_____+_____+_____
+_____+_____+_____+_____ = _____kg/hr

3. HYDROGEN

Σ in = _____+_____+_____+_____ = _____kg/hr

Σ out = _____+_____+_____+_____+_____+_____
+_____+_____+_____+_____ = _____kg/hr

4. OXYGEN

Σ in = _____+_____+_____+_____ = _____kg/hr

Σ out = _____+_____+_____+_____+_____+_____
+_____+_____+_____+_____ = _____kg/hr

5. NITROGEN

Σ in = _____+_____+_____+_____ = _____kg/hr

Σ out = _____+_____+_____+_____+_____+_____
+_____+_____+_____+_____ = _____kg/hr

MASS BALANCE - PERCENT CLOSURES

1. OVERALL PCCL(1) $= \dfrac{(\sum OV_{out})(100)}{(\sum OV_{in})} = \dfrac{(\quad)(100)}{(\quad)} = \_\_\_\_\%$

2. CARBON PCCL(2) $= \dfrac{(\sum C_{out})(100)}{(\sum C_{in})} = \dfrac{(\quad)(100)}{(\quad)} = \_\_\_\_\%$

3. HYDROGEN PCCL(3) $= \dfrac{(\sum H_{out})(100)}{(\sum H_{in})} = \dfrac{(\quad)(100)}{(\quad)} = \_\_\_\_\%$

4. OXYGEN PCCL(4) $= \dfrac{(\sum O_{out})(100)}{(\sum O_{in})} = \dfrac{(\quad)(100)}{(\quad)} = \_\_\_\_\%$

5. NITROGEN PCCL(5) $= \dfrac{(\sum N_{out})(100)}{(\sum N_{in})} = \dfrac{(\quad)(100)}{(\quad)} = \_\_\_\_\%$

TABLE F-1

SUMMARY OF MASS BALANCE CALCULATIONS

GASIFIER INPUT	OVERALL kg/hr	%	CARBON kg/hr	%	HYDROGEN kg/hr	%	OXYGEN kg/hr	%	NITROGEN kg/hr	%
1. Dry Feed										
2. Moisture in Feed										
3. Dry Air										
4. Moisture in Air										
5. Other										
TOTAL										
GASIFIER OUTPUT										
1. Dry Gas										
2. Particulates										
3. Tar										
4. Water Sol. Org.										
5. Moisture in Gas										
6. Char										
7. Moisture in Char										
8. Fly Ash										
9. Moisture in Fly Ash										
10. Other										
TOTAL										

PERCENT CLOSURE

	INPUT kg/hr			OUTPUT kg/hr		CLOSURE %
	FUEL	AIR	OTHERS	DRY GAS	OTHERS	
OVERALL						
CARBON						
HYDROGEN						
OXYGEN						
NITROGEN						

APPENDIX G

WORKSHEETS FOR ENERGY BALANCE CALCULATIONS

ENERGY BALANCE CALCULATIONS

The following data are required, in addition to data from the mass balance calculations.

SYMBOL	DEFINITION AND UNITS	VALUE
ENTHALPIES		
H_{air}	= Enthalpy of H_2O in air feed at air temperature, J/kg	_____
H_{feed}	= Enthalpy of H_2O in feed at feed temperature, J/kg	_____
H_{ref}	= Enthalpy of H_2O in air feed at 15°C, J/kg	63,000
H_{stk}	= Enthalpy of steam at sampling temperature and pressure, J/kg	_____
SPECIFIC HEATS		
AC_p	= Specific heat at constant pressure of feed air, J/kg°C	_____
CHC_p	= Specific heat at constant pressure of char, J/kg°C	_____
C_{pdry}	= Average specific heat of dry gas at constant pressure, J/kg°C	_____
C_pF_{dry}	= Specific heat at constant pressure of dry feed, J/kg°C	_____
FAC_p	= Specific heat at constant pressure of fly ash, J/kg°C	_____
PC_p	= Specific heat at constant pressure of particulates, J/kg°C	_____
TC_p	= Specific heat at constant pressure of tar, J/kg°C	_____
$WSOC_p$	= Specific heat at constant pressure of water soluble organics, J/kg°C	_____

ENERGY BALANCE CALCULATIONS

SYMBOL		DEFINITION AND UNITS	VALUE
HEATS OF COMBUSTION			
$CH_{H\ of\ C}$	=	Heat of combustion of char, J/kg	
$FA_{H\ of\ C}$	=	Heat of combustion of fly ash, J/kg	
$G_{H\ of\ C}$	=	Standard higher heat of combustion of dry producer gas, J/m^3	
HF_{dry}	=	Standard higher heat of combustion at 1 atm and 25°C of dry feed, J/kg	
$P_{H\ of\ C}$	=	Heat of combustion (higher heating value) of particulates, J/kg	
$T_{H\ of\ C}$	=	Heat of combustion of tar, J/kg	
$WSO_{H\ of\ C}$	=	Heat of combustion of water soluble organics, J/kg	
TEMPERATURES			
$T_{air\ in}$	=	Temperature of feed air, °C	
T_{ref}	=	Reference temperature, 15°C	15
T_{stk}	=	Temperature of gas at sampling point, °C	
OTHER			
$E_{in}(n)$	=	Energy input of stream "n", J/hr	
$E_{out}(n)$	=	Energy output of stream "n", J/hr	
GE	=	Gross efficiency of gasifier system	
NE	=	Net efficiency of gasifier system	
HL	=	Heat loss from process to sampling point, J/hr	
PCCL	=	Percent closure	

ENERGY BALANCE

IN:

1. Heat of Combustion of Dry Feed

$E_{in}(1) = (F_{dry})(HF_{dry})$

= (_____kg/hr)(_____J/kg)

= _____J/hr

2. Process Energy Input (Electro-Mechanical)

$E_{in}(2) = E_1 + E_2 + E_3 + \ldots$

= _____J/hr

3. Enthalpy of Humid Process Air

$E_{in}(3) = (A_{dry})(AC_p)(T_{air\ in}-T_{ref}) + (A_{dry})(H)(H_{air}-H_{ref})$

= (_____kg/hr)(_____J/kg°C)(___°C - 15°C) +
(_____kg/hr)(_____)(_____- 63,000 J/kg)

= _____+_____

= _____J/hr

4. Enthalpy of Moisture in Feed

$E_{in}(4) = (F_{wet})(WF)(H_{feed}-H_{ref})$

= (_____kg/hr)(_____)(_____ - 63,000 J/kg)

= _____J/hr

5. Sensible Heat of Dry Feed

$E_{in}(5) = (F_{dry})(C_pF_{dry})(T_{feed}-T_{ref})$

= (_____kg/hr)(_____J/kg °C)(___°C - 15°C)

= _____J/hr

ENERGY BALANCE

OUT:

1. Heat of Combustion of Dry Producer Gas

$E_{out}(1) = (G_{dry})(G_{H\ of\ C})$

$= (\_\_\_\_\_ m^3/hr)(\_\_\_\_\_ J/m^3)$

$= \_\_\_\_\_ J/hr$

2. Sensible Heat of Dry Producer Gas

$E_{out}(2) = (G_{dry})(D)(C_{pdry})(T_{stk}-T_{ref})$

$= (\_\_\_\_\_ m^3/hr)(\_\_\_\_\_ kg/m^3)(\_\_\_\_\_ J/kg°C)(\_\_\_ °C - 15°C)$

$= \_\_\_\_\_ J/hr$

3. Enthalpy of Water in Producer Gas

$E_{out}(3) = (G_{dry})(WC)(H_{stk}-H_{ref})$

$= (\_\_\_\_\_ m^3/hr)(\_\_\_\_\_ kg/m^3)(\_\_\_\_\_ J/kg - 63{,}000\ J/kg)$

$= \_\_\_\_\_ J/hr$

4. Heat of Combustion of Particulates

$E_{out}(4) = (G_{dry})(PC)(P_{H\ of\ C})$

$= (\_\_\_\_\_ m^3/hr)(\_\_\_\_\_ kg/m^3)(\_\_\_\_\_ J/kg)$

$= \_\_\_\_\_ J/hr$

5. Heat of Combustion of Tars

$E_{out}(5) = (G_{dry})(TC)(T_{H \text{ of } C})$

$= (\_\_\_\_\_ m^3/hr)(\_\_\_\_\_ kg/m^3)(\_\_\_\_\_ J/kg)$

$= \_\_\_\_\_ J/hr$

6. Heat of Combustion of Water Soluble Organics

$E_{out}(6) = (G_{dry})(WSOC)(WSOC_{H \text{ of } C})$

$= (\_\_\_\_\_ m^3/hr)(\_\_\_\_\_ kg/m^3)(\_\_\_\_\_ J/kg)$

$= \_\_\_\_\_ J/hr$

7. Sensible Heat of Particulates, Tar and Water Soluble Organics

$E_{out}(7) = [(PC_p)(PC) + (TC_p)(TC) + (WSOC_p)(WSOC)]\,[(G_{dry})(T_{stk} - T_{ref})]$

$= [(\_\_\_\_\_)(\_\_\_\_\_)+(\_\_\_\_\_)(\_\_\_\_\_)+(\_\_\_\_\_)(\_\_\_\_\_)]$
$[(\_\_\_\_\_)(\_\_\_ °C - 15°C)]$

$= [\_\_\_\_\_ J/m^3][\_\_\_\_\_ m^3/hr]$

$= \_\_\_\_\_ J/hr$

8. Heat of Combustion of Char

$E_{out}(8) = (CH_{dry})(CH_{H \text{ of } C})$

$= (\_\_\_\_\_ kg/hr)(\_\_\_\_\_ J/kg)$

$= \_\_\_\_\_ J/hr$

9. Heat of Combustion of Fly Ash

$E_{out}(9) = (FA_{dry})(FA_{H\ of\ C})$

$= (\_\_\_\_\_ kg/hr)(\_\_\_\_\_ J/kg)$

$= \_\_\_\_\_ J/hr$

10. Sensible Heat of Char and Fly Ash

$E_{out}(10) = (CHC_p)(CH_{dry}) + (FAC_p)(FA_{dry})$

$= (\_\_\_\_\_ J/kg)(\_\_\_\_\_ kg/hr) + (\_\_\_\_\_ J/kg)(\_\_\_\_\_ kg/hr)$

$= \_\_\_\_\_ + \_\_\_\_\_$

$= \_\_\_\_\_ J/hr$

11. Heat Loss from Process

$E_{out}(11) = HL$

$= \_\_\_\_\_ J/hr$

ENERGY BALANCE

Energy In		J/hr	%
1.	Heat of Combustion, Feed		
2.	Process Energy Input		
3.	Enthalpy, Process Air		
4.	Enthalpy, Feed Moisture		
5.	Sensible Heat, Dry Feed		
6.	Other		
	TOTAL		

Energy Out			
1.	Heat of Combustion, Dry Gas		
2.	Sensible Heat, Dry Gas		
3.	Enthalpy, Gas Moisture		
4.	Heat of Combustion, Particulates		
5.	Heat of Combustion, Tar		
6.	Heat of Combustion, Water Soluble Organics		
7.	Sensible Heat, Particulates, Tar and WSO		
8.	Heat of Combustion, Char		
9.	Heat of Combustion, Fly Ash		
10.	Sensible Heat of Char and Fly Ash		
11.	Process Heat Loss		
12.	Other		
	TOTAL		

PERCENT CLOSURE

$$PCCL = \frac{(\text{Total Energy Out})(100)}{(\text{Total Energy In})}$$

$$= \frac{(\qquad)(100)}{(\qquad)} = \_\_\_\_\%$$

GROSS EFFICIENCY

$$GE = \frac{(\text{Total Raw Producer Gas Energy Out})(100)}{(\text{Total Energy In})}$$

$$= \frac{(\sum E_{out}\,(1 - \text{"n"}))(100)}{(\sum E_{in})}$$

$$= \frac{(\qquad)(100)}{(\qquad)} = \_\_\_\_\%$$

NET EFFICIENCY

$$NE = \frac{(\text{Heating Value of Gas Out})(100)}{(\text{Total Energy In})}$$

$$= \frac{(E_{out}\ 1)(100)}{(\sum E_{in})}$$

$$= \frac{(\qquad)(100)}{(\qquad)} = \_\_\_\_\%$$

TABLE G-1

SUMMARY OF ENERGY BALANCE CALCULATIONS

	INPUT (MJ/hr)						OUTPUT (MJ/hr)						
RUN NO.	FUEL	%	AIR	%	OTHERS	%	CLEAN GAS	%	TAR PARTICUL. CONDEN.	%	OTHERS	%	CLOSURE %
1 2 3													
													GROSS ENERGY BALANCE %
1 2 3											-[a] - -	- - -	
													NET EFFICIENCY %
1 2 3							b	100 100 100	- - -	- - -	-[a] - -	- - -	

[a]component does not contribute to this energy calculation.

[b]heat of combustion; dry, clean gas

APPENDIX H

PRODUCER GAS ANALYSIS COMPUTER PROGRAM

PRODUCER GAS ANALYSIS COMPUTER PROGRAM

```
 0  GOTO 1000: REM SKIP SUBROUTINE SPACE
 10  REM ****************************
 15  REM *                          *
 20  REM *     PRODUCER GAS         *
 25  REM *       ANALYSIS           *
 30  REM *                          *
 35  REM * PREPARED FOR APPLE II    *
 40  REM * WITH EPSON DOT MATRIX    *
 45  REM * PRINTER, PKASO BOARD,    *
 50  REM *    AND DISK DRIVE        *
 55  REM *       AUG 1982           *
 60  REM *      L PHILLIPS          *
 65  REM ****************************
1000  REM
                    INITIALIZE

1010  HOME : INVERSE : HTAB 10: PRINT " CHEMS GAS ANALYSIS ": NORMAL : POKE 34,2: REM POKE SETS TEXT WINDOW
1100 D$ = CHR$ (4):I$ =  CHR$ (9)
1150 ABIT = 1E - 20: REM USED TO PREVENT DIVIDE BY 0 ERRS
1300  REM ------SET DEFAULTS FOR PROB PARAMS
1310 UNITS = 1:K1 = 1:K2 = 1:K3 = 1: REM METRIC UNITS
1320 T = 288:P = 101300: REM T,P BASIS
1500  REM ------READ GAS DATA @ LINE 20000
1510  READ NGAS
1520  FOR I = 1 TO NGAS: READ NM$(I),FRM$(I),MW(I),MWV(I),LMV(I),A(I),C(I),H(I),O(I),N(I),S(I),VA(I),VB(I),VC(I),VD(I): NEXT

2000  REM

                    ** MENU ** (ALL ROUTINES RETURN HERE)


2100  HOME : HTAB 10: PRINT "CHOOSE:": PRINT
2110  PRINT "1) SELECT OPTIONS": PRINT
2120  PRINT "2) ENTER CONCENTRATIONS": PRINT
2130  PRINT "3) CALCULATE & PRINT REPORT": PRINT
2140  PRINT "4) PRINT GAS DATA": PRINT
2150  PRINT "5) "
2160  PRINT "6) "
2170  PRINT "7) COMPUTE INTEGRAL AVG CP"
2180  PRINT "8) ": PRINT
2190  PRINT "9) QUIT": PRINT
2200  HTAB 20: INPUT "WHICH? ";CHOICE$:CHOICE = VAL (CHOICE$)
2210  IF CHOICE > 255 OR CHOICE < 0 THEN 2000
2220  ON CHOICE GOTO 3000,4000,8000,7000,4500,4500,6000,4500,10000: GOTO 2000
3000  REM
                    SET PROGRAM PARAMETERS

3100  REM ------SELECT UNITS
3110  HOME : PRINT "CHOOSE:  1) METRIC UNITS": INPUT "        2) ENGINEERING UNITS ";UNITS
3120  IF UNITS <  > 1 AND UNITS <  >2 THEN 3110: REM INVALID RESPONSE
3130  IF UNITS = 1 THEN K1 = 1:K2 = 1:K3 = 1: GOTO 3200: REM METRIC SELECTED, CONTINUE
3140  IF UNITS = 2 THEN K1 = 6.2426E - 2:K2 = 2.6836E - 5:K3 = 7.7430E - 4: REM ENG SEL'D: K1=KB/M3->LB/FT3, K2=J/M3->BTU/FT3
    , K3=J/KGK->BTU/LBF
3200  REM ------SELECT T,P BASIS
3210  HOME : PRINT "BASIS IS ";T;" K, ";P;" PASCALS": PRINT "(101300 PA = 1 ATM)": PRINT
3220  INPUT "OK" (Y/N) ";A$: IF  LEFT$ (A$,1) = "Y" THEN 3999: REM CONTINUE
3230  INPUT "NEW TEMP? (KELVIN) ";T
3240  INPUT "NEW PRESS? (PASCALS) ";P
3999  GOTO 2000: REM MENU
4000  REM
                    INPUT GAS CONC'S

4005 AA = 0:BB = 0:CC = 0:DD = 0: REM FOR INT AV CP ROUTINE
```

```
4010  HOME : PRINT "USING 'RETURN' WILL OMIT GAS FROM REPORT": PRINT : PRINT
4100  FOR I = 1 TO NGAS
4150  PRINT NM$(I);"  ";FRM$(I)
4160  INPUT "VOLUME % CONC'N? ";PCT$:PCT(I) =  VAL (PCT$): PRINT
4170 OK(I) = (PCT$ <  ) "");: REM OK=1 FOR EA GAS FOR WHICH REPORT DESIRED
4200  NEXT I
4250  HOME : INPUT "SAMPLE NAME? ";SAM$
4499  GOTO 2000: REM MENU
4500  REM (SPARE ROUTINE SPACE)
4501  GOTO 2000: REM MENU
6000  REM
                    INTEGRAL-AVG CP

6050  IF  NOT (VA + VB + VC + VD) THEN  PRINT "DO CALCULATIONS FIRST...";: GET A$: PRINT A$: GOTO 2000: REM ABORT IF NO CALCS

6100  HOME : INPUT "T1? (K) ";T1: INPUT "T2? (K) ";T2
6120  DEF  FN CP(T) = (VA + T + VB / 2 * T ^ 2 + VC / 3 * T ^ 3 + VD / 4 * T ^ 4)
6130 AVG = ( FN CP(T2) -  FN CP(T1)) / (T2 - T1 * ABIT)
6150  PRINT D$"PR#1": PRINT : PRINT : REM PRINTER ON
6160  PRINT "INTEGRAL AVG CP BETWEEN "T1" & "T2" = ";AVG;"  J/KG K"
6200  PRINT : PRINT : PRINT D$"PR#0": REM PRINTER OFF
6250  GOTO 2000: REM MENU
7000  REM
                    PRINT GAS DATA

7050  PRINT D$"PR#1": PRINT  CHR$ (15): PRINT I$"132N": PRINT  CHR$ (12): REM  PRINTER ON, 132 CONDENSED CHARS, FORM-FEED
7080  PRINT  SPC( 24);"MOLAR     HIGHER    LOWER     GAS       MASS      MASS      MASS      MASS      MASS"
7090  PRINT  SPC( 24);"MASS      HEATING   HEATING   CONSTANT  FRACTION  FRACTION  FRACTION  FRACTION  FRACTION"
7100  PRINT  SPC( 24);"          VALUE     VALUE     R         CARBON    HYDROGEN  OXYGEN    NITROGEN  SULFUR"
7105  PRINT
7110  PRINT  SPC( 25);"KG/MOLE   J/KG      J/KG      J/KG K": PRINT
7130  FOR I = 1 TO NGAS
7140  PRINT NM$(I);I0"16T"FRM$(I);I0"24T"MW(I);I0"34T"HHV(I);I0"44T"LHV(I);
7150  PRINT I0"54T"R(I);I0"64T"C(I);I0"74T"H(I);I0"84T"O(I);I0"94T"N(I);I0"104T"S(I)
7170  NEXT I
7200  PRINT : PRINT : PRINT "VIRIAL COEFICIENTS FOR CP =  A + BT + CT^2 + DT^3  (JOULES/KG K, T IN KELVIN)": PRINT
7210  PRINT  SPC( 25);"A";I0"40TB *10^2";I0;"55TC *10^5";I0;"70TD *10^9": PRINT
7230  FOR I = 1 TO NGAS
7240  PRINT NM$(I);I0"16T";FRM$(I);I0"25T";VA(I);I0"40T";VB(I);I0"55T";VC(I);I0"70T";VD(I)
7250  NEXT I
7390  PRINT D$"PR#0": REM PRINTER OFF
7400  GOTO 2000: REM MENU
8000  REM
                    CALCULATIONS

8020  REM -----CALC MASS OF EACH GAS & ITS ELEMENTS
8030  FOR I = 1 TO NGAS
8035 MASS = PCT(I) / 100 / R(I) * P / T * K1
8040 CCNC(I) = MASS * C(I)
8060 HCNC(I) = MASS * H(I)
8080 OCNC(I) = MASS * O(I)
8100 NCNC(I) = MASS * N(I)
8120 SCNC(I) = MASS * S(I)
8140 TCNC(I) = MASS
8180  NEXT I
8200  REM -----SUM THE I & ELEMENTAL CONTRIBUTION (IE, SUM DOWN THE COLUMNS)
8210 PCT = ZERO:TC = IE:TH = IE:TO = IE:TN = IE:TS = IE:CNC = IE
8220  FOR I = 1 TO NGAS
8240 PCT = PCT + PCT(I):TC = TC + CCNC(I):TH = TH + HCNC(I):TO = TO + OCNC(I):TN = TN + NCNC(I):TS = TS + SCNC(I):CNC = CNC +
     TCNC(I)
8260  NEXT I
8280  REM -----CALC OVERALL SP HT VIRIAL CSTS
8290 VA = IE:VB = IE:VC = IE:VD = IE
8300  FOR I = 1 TO NGAS
8310 VA = VA + VA(I) * TCNC(I):VB = VB + VB(I) * TCNC(I):VC = VC + VC(I) * TCNC(I):VD = VD + VD(I) * TCNC(I)
8320  NEXT I
```

```
8330 VA = VA / (CNC + ABIT):VB = VB + 1E - 2 / (CNC + ABIT):VC = VC + 1E - 5 / (CNC + ABIT):VD = VD + 1E - 9 / (CNC + ABIT)
8500  REM ------CALC HEAT OF COMBUSTION FOR EACH GAS
8520  FOR I = 1 TO NGAS:COMB(I) = TCNC(I) * HHV(I): NEXT
8550  REM SUM THE OVERALL H OF C
8560 COMB = ZE: REM ZERO SUM
8570  FOR I = 1 TO NGAS:COMB = COMB + COMB(I): NEXT
8800  REM ------CONSTRUCT A MASS PERCENTAGE TABLE
8810  DEF  FN PC(II) = II / (CNC + ABIT) * 100: REM CALCS %-AGE OF OVERALL FOR EACH SPECIES
8820  FOR I = 1 TO NGAS
8830 TABLE(I,1) = PCT(I): REM VOL %
8840 TABLE(I,2) =  FN PC(CCNC(I)):TABLE(I,3) =  FN PC(HCNC(I)):TABLE(I,4) =  FN PC(OCNC(I))
8850 TABLE(I,5) =  FN PC(NCNC(I)):TABLE(I,6) =  FN PC(SCNC(I)):TABLE(I,7) =  FN PC(TCNC(I))
8860  NEXT I
8870 TABLE(I,1) = PCT:TABLE(I,2) =  FN PC(TC):TABLE(I,3) =  FN PC(TH):TABLE(I,4) =  FN PC(TO):TABLE(I,5) =  FN PC(TN):TABLE(I
    ,6) =  FN PC(TS):TABLE(I,7) =  FN PC(CNC)
9000  REM
                        NOW, PRINT REPORT

9050  PRINT D$"PR#1": PRINT  CHR$ (15): PRINT I$"132N": PRINT  CHR$ (12): REM PRINTER ON, 132 CONDENSED CHARS, FORM-FEED
9075  PRINT SAV$: PRINT
9080  PRINT "BASIS = ";T;" K & ";P;" PASCALS": PRINT
9120  PRINT I$"50T";"MASS CONCENTRATION  ";: IF UNITS = 1 THEN  PRINT "(KG/CU M)": PRINT
9125  IF UNITS = 2 THEN  PRINT "(LB/CU FT)": PRINT
9130  PRINT I$;"25T";"VOL %          C             H             O             N             S             TOTAL": PRINT

9140  FOR I = 1 TO NGAS
9150  IF OK(I) THEN  PRINT NM$(I);I$;"16T";FRM$(I);I$;"25T";PCT(I);I$;"40T";CCNC(I) * K1;;I$;"55T";HCNC(I) * K1;
9160  IF OK(I) THEN  PRINT I$;"70T";OCNC(I) * K1;I$;"85T";NCNC(I) * K1;I$;"100T";SCNC(I) * K1;I$"115T";TCNC(I) * K1
9170  NEXT I
9175  PRINT
9180  PRINT "TOTAL";I$;"16T";FRM$(I);I$;"25T";PCT;I$;"40T";TC;I$;"55T";TH;;I$;"70T";TO;I$;"85T";TN;I$;"100T";TS;I$"115T";CNC
9200  PRINT : PRINT : PRINT : PRINT I$;"50T";"MASS CONCENTRATION %": PRINT
9210  PRINT I$;"25T";"VOL %          C             H             O             N             S             TOTAL": PRINT

9215  DEF  FN RD(II) =  INT (II * 100 + .5) / 100: REM ROUNDS TO 2 DEC PTS
9217  FOR I = 1 TO NGAS
9220  IF OK(I) THEN  PRINT NM$(I);I$"16T";FRM$(I);: FOR J = 1 TO 7: POKE 36,15 + J * 10: PRINT  FN RD(TABLE(I,J));: NEXT J: PRINT
    : REM POKE WORKS LIKE A TAB
9225  REM POKE WORKS LIKE A TAB
9230  NEXT I
9270  PRINT : PRINT "TOTAL";: FOR J = 1 TO 7: POKE 36,15 + J * 10: PRINT  FN RD(TABLE(I,J));: NEXT J: PRINT
9310  PRINT : PRINT : PRINT : PRINT "STD HIGHER HEAT OF COMBUSTION  ";: IF UNITS = 1 THEN  PRINT "(J/CU M)"
9315  IF UNITS = 2 THEN  PRINT "(BTU/CU FT)"
9317  PRINT
9320  FOR I = 1 TO NGAS
9340  IF OK(I) THEN  PRINT FRM$(I)I$"16T"COMB(I) * K2
9360  NEXT I
9380  PRINT : PRINT "TOTAL"I$"16T";COMB * K2: PRINT : PRINT : PRINT
9400  PRINT "HEAT CAPACITY (CP) = ";VA * K3;" + ";VB * K3;" T + ";VC * K3;" T^2 + ";VD * K3;" T^3  ";: IF UNITS = 1 THEN  PRINT
    "(J/KG K)"
9410  IF UNITS = 2 THEN  PRINT "(BTU/LB DEG RANKIN  OR  BTU/LB DEG F)"
9420  PRINT I$"40T(TEMPERATURE IN KELVIN)"
9950  PRINT D$"PR#0": REM PRINTER OFF  .
9960  GOTO 2000: REM MENU
10000  REM
                        EXIT ROUTINE...

10010  POKE 34,0: REM  RESET TEXT WINDOW
10020  HOME : PRINT "END OF PROGRAM": END
20000  REM
                        GAS DATA

20005  DATA  9: REM # OF GASES IN LIST, MUST BE KEPT UP TO DATE
20010  DATA METHANE,CH4,.016,55500000,50010000,520,.75,.25,0,0,0,1238,312.8,78.98, - 685.9
20020  DATA CARBON DIOXIDE,CO2,.044,0,0,189,.2727,0,.7273,0,0,607.3,95.95,-32.35,0
20030  DATA ETHENE(=YLENE),C2H4,.028,50464000,1E33,294.3,.8571,.1429,0,0,0,140.7,356.7,-297.1,629
```

```
20040  DATA ETHANE,C2H6,.030,51870000,47470000,277,.8,.2,0,0,0,229.3,373.4,-213.15,241.9
20050  DATA OXYGEN,02,.032,0,0,260,0,0,1,0,0,879.6,19.66,-2.340,0
20060  DATA NITROGEN,N2,.028,0,0,295,0,0,0,1,0,974.2,22.2,-3.389,0
20070  DATA CARBON MONOXIDE,CO,.028,10100000,10100000,297,.4286,0,.5714,0,0,967.3,23.38,-3.363,0
20080  DATA HYDROGEN,H2,.02016,142000000,120000000,4120,0,1,0,0,0,13323,215.5,-16.18,0
20090  DATA PROPANE,C3H8,.044,50360000,46360000,183.7,.8182,.1818,0,0,0,-91.65,490.3,-336.1,718.8
```

		MOLAR MASS	HIGHER HEATING VALUE	LOWER HEATING VALUE	GAS CONSTANT R	MASS FRACTION CARBON	MASS FRACTION HYDROGEN	MASS FRACTION OXYGEN	MASS FRACTION NITROGEN	MASS FRACTION SULFUR
		KG/MOLE	J/KG	J/KG	J/KG K					
METHANE	CH4	.016	55500000	50010000	520	.75	.25	0	0	0
CARBON DIOXIDE	CO2	.044	0	0	189	.2727	0	.7273	0	0
ETHENE(=YLENE)	C2H4	.028	50464000	1E+33	294.5	.8571	.1429	0	0	0
ETHANE	C2H6	.03	51870000	47470000	277	.8	.2	0	0	0
OXYGEN	02	.032	0	0	260	0	0	1	0	0
NITROGEN	N2	.028	0	0	295	0	0	0	1	0
CARBON MONOXIDE	CO	.028	10100000	10100000	297	.4286	0	.5714	0	0
HYDROGEN	H2	.02016	142000000	120000000	4120	0	1	0	0	0
PROPANE	C3H8	.044	50360000	46360000	183.7	.8182	.1818	0	0	0

VIRIAL COEFICIENTS FOR CP = A + BT + CT^2 + DT^3 (JOULES/KG K, T IN KELVIN)

		A	B *10^2	C *10^5	D *10^9
METHANE	CH4	1238	312.8	78.98	-485.3
CARBON DIOXIDE	CO2	607.3	95.95	-32.35	0
ETHENE(=YLENE)	C2H4	140.7	356.7	-297.1	829
ETHANE	C2H6	229.3	373.4	-213.15	241.9
OXYGEN	02	879.6	19.66	-2.34	0
NITROGEN	N2	974.2	22.2	-3.389	0
CARBON MONOXIDE	CO	967.3	23.38	-3.363	0
HYDROGEN	H2	13323	215.5	-16.18	0
PROPANE	C3H8	-91.65	490.3	-336.1	718.8

APPENDIX I

EXAMPLE OF GAS ANALYSIS PROGRAM OUTPUT

PRODUCER GAS ANALYSIS PROGRAM OUTPUT

. .

86515 = 298 K & 101300 PASCALS

MASS CONCENTRATION (KG/CU M)

		VOL %	C	H	O	N	S	TOTAL
METHANE	CH4	2.82	.0143861899	4.76872997E-03	0	0	0	.0190749199
CARBON DIOXIDE	CO2	17.18	.0871893522	0	.232536912	0	0	.319726264
ETHENE(=YLENE)	C2H4	1.1	.0112604524	1.87739896E-03	0	0	0	.0131378514
ETHANE	C2H6	.09	9.14259928E-04	2.28564982E-04	0	0	0	1.14282491E-03
OXYGEN	O2	1.77	0	0	.0229451122	0	0	.0229451122
NITROGEN	N2	55.97	0	0	0	.667344751	0	.667344751
CARBON MONOXIDE	CO	9.16	.0464952263	0	.061986372	0	0	.108481575
HYDROGEN	H2	5.02	0	4.28571669E-03	0	0	0	4.28571669E-03
PROPANE	C3H8	.04	6.26653209E-04	1.39239249E-04	0	0	0	7.65892458E-04
TOTAL		93.15	.160792111	.0112996499	.318468396	.667344751	0	1.15790491

MASS CONCENTRATION %

		VOL %	C	H	O	N	S	TOTAL
METHANE	CH4	2.82	1.24	.41	0	0	0	1.65
CARBON DIOXIDE	CO2	17.18	7.53	0	20.08	0	0	27.61
ETHENE(=YLENE)	C2H4	1.1	.97	.16	0	0	0	1.13
ETHANE	C2H6	.09	.08	.02	0	0	0	.1
OXYGEN	O2	1.77	0	0	2.07	0	0	2.07
NITROGEN	N2	55.97	0	0	0	57.63	0	57.63
CARBON MONOXIDE	CO	9.16	4.02	0	5.35	0	0	9.37
HYDROGEN	H2	5.02	0	.37	0	0	0	.37
PROPANE	C3H8	.04	.05	.01	0	0	0	.07
TOTAL		93.15	13.89	.98	27.5	57.63	0	100

STD HIGHER HEAT OF COMBUSTION (J/CU M)

CH4	1050458.05
CO2	0
C2H4	662988.53
C2H6	59278.3281
O2	0
N2	0
CO	1095663.91
H2	608571.77
C3H8	38570.3442
TOTAL	3523730.93

HEAT CAPACITY (CP) = 909.441754 + .351754192 T + -1.38437242E-04 T**2 + -3.44171208E-09 T**3 (J/KG K)
(TEMPERATURE IN KELVIN)

INTEGRAL AVG CP BETWEEN 298 & 874 = 1178.47169 J/KG K

APPENDIX J

RFL MODEL 70A
PROPORTIONAL TEMPERATURE CONTROLLER

INSTRUCTION SHEET

011873C

RFL Industries, Inc., Boonton, New Jersey 07005

RFL MODEL 70A
PROPORTIONAL TEMPERATURE CONTROLLER

DESCRIPTION

The RFL Model 70A is a "stepless", full-wave phase firing temperature controller capable of controlling as accurately as ±.05°C in many applications. Resistive loads from 1 to 15 amps, 115 or 230 Vac 50/60 Hz can be controlled. Set point adjustment is achieved via internal screwdriver accessible Coarse and Fine controls or with a remote 10,000 ohm potentiometer (RFL #42060 or equiv.) A Gain adjustment is provided enabling the bandwidth (sensitivity) of the controller to match the thermal dynamics of the complete system. The all solid state design requires minimum maintenance when the unit is operated within its specified ratings.

SPECIFICATIONS

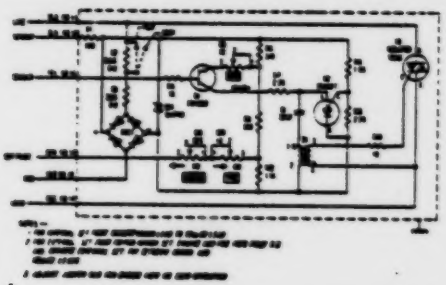
Voltage and Current Ratings: Single phase, 50/60 Hz 115 or 230V line @ 15A max. Field selectable.

(Above ratings apply at controller case temperature not exceeding 60°C. See derating curve for operational ratings at higher case temperatures.)

Proportional Controlling Band: 7% to 2% of range in degrees, depending on setting of Gain control.

Accuracy: To ±0.05°C of set point with stable line voltage and ambient temperature.

Range: -70°C to +450°C (-90°F to +842°F) using RFL sensors.

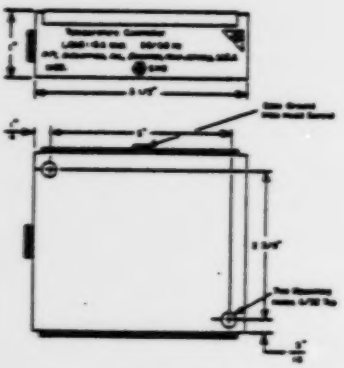


Schematic Diagram of RFL Model 70A

SENSORS

The Model 70A requires a negative temp. coefficient resistance sensor operating within the range of 8000 to 100 ohms. The following RFL sensors are recommended:

RFL #	RANGE	RESISTANCE ±20%
27687-15	-70°C to +10°C (-90°F to +50°F)	100 ohms @ 25°C
27687-3	-5°C to +120°C (+20°F to +250°F)	2,000 ohms @ 25°C
27687-5	+30°C to +160°C (+90°F to +320°F)	10,000 ohms @ 25°C
27687-7	+80°C to +230°C (+175°F to +450°F)	50,000 ohms @ 25°C
27687-13	+220°C to +325°C (+428°F to +617°F)	10 megohm @ 25°C
27687-18	+300°C to +450°C (+572°F to +842°F)	310,000 ohms @ 125°C



Case and Mounting Dimensions

INSTALLATION

WARNING: Disconnect power before installing or making any connections to the controller to prevent the possibility of hazardous electrical shock to personnel. Refer to installation drawings before connecting the controller.

POWER CONNECTIONS

Line: Connect the black and the white controller leads to the line, observing hot and neutral sides as shown in the installation drawings.

Load: Connect the load to the controller red lead and the junction of the controller white lead and the line connection.

Ground: Connect an earth ground to the controller case at the hex-head screw marked GND. Use #14 or larger wire.

LINE DISCONNECT: A suitable disconnect circuit must be present in the hot side or sides of the line; that is, a switch or circuit breaker. If a circuit breaker is not used then a properly rated fuse (no higher than 15 amperes) should be installed in addition to the switch.

OPERATING VOLTAGE

Remove the controllers cover and examine the operating voltage jumper bar. (See diagram). Using pliers, move this bar into the desired position. All stock units are factory set for 230 Vac operation.

SENSOR AND SET POINT CONNECTIONS

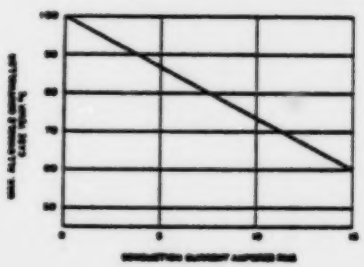
Sensor: (Using Controller Internal Set Point) Connect both the yellow and the brown controller leads to one side of the sensor; connect the controller blue lead to the other side of the sensor.

(Using External Set Point Control) Connect the controller blue lead to one side of the sensor and the controller yellow lead to the other side of the sensor. Connect the external set point control between the controller brown lead and the junction of the controller yellow lead and sensor connection.

NOTE: The external set point control shaft and bushing should be connected to an earth ground to prevent the possibility of shock hazard.

MOUNTING

Do not mount the controller on a thermally insulated surface such as a wooden bench or wall, fiberglass, plastic, etc. to prevent excessive case temperature rise. Under no conditions should the case temperature be allowed to rise above 100°C (See Derating Curve). Whenever possible, the controller should be mounted in a vertical position, with wire leads exiting from the bottom. Additional heat sinking will be required for high load operation. (Above 6 Amps).



Derating Curve

CONTROLLER ADJUSTMENT – INTERNAL SET POINT

1. Turn the COARSE, FINE, and GAIN controls fully counterclockwise, then back each control off approximately one-eighth of a turn.

2. Connect a voltage monitor (voltmeter, lamp, or other indicating device) across the load leads with a minimum of 1 amp load connected.

3. Turn GAIN adjustment one-quarter turn clockwise.

4. Adjust the COARSE and FINE controls for desired temperature. Note: The voltage across the load will decrease as the temperature set point is approached.

5. After the controller has stabilized at the desired temperature, increase (clockwise) the "GAIN" adjustment in small steps, giving the controller time to stabilize between adjustments. Continue to increase the GAIN setting unless the controllers output begins to oscillate from full on to full off. Should this occur, back off the GAIN until the controllers output once again becomes steady. NOTE: Adjusting the GAIN setting will normally cause the set point to change.

6. After the GAIN control has been adjusted properly, the indicator may be removed from across the load. Reset fine control for exact temperature desired.

CONTROLLER ADJUSTMENT – EXTERNAL SET POINT

Turn "COARSE" and "FINE" adjustments fully clockwise. Follow above procedure using the external dial whenever the "COARSE" and "FINE" are referred to.

NOTE: If the controller is not holding temperature steady, or not enough heating is obtained, first check for external conditions which may prevent the controller from operating correctly. Examples are: low input voltage to the controller; improper power wire size; damaged heater or sensor; or poor sensor thermal contact or location.

A properly operating controller will yield the following results: With the yellow and the blue leads open, the controller output will be maximum. With the yellow and the blue leads shorted, the controller output will be zero.

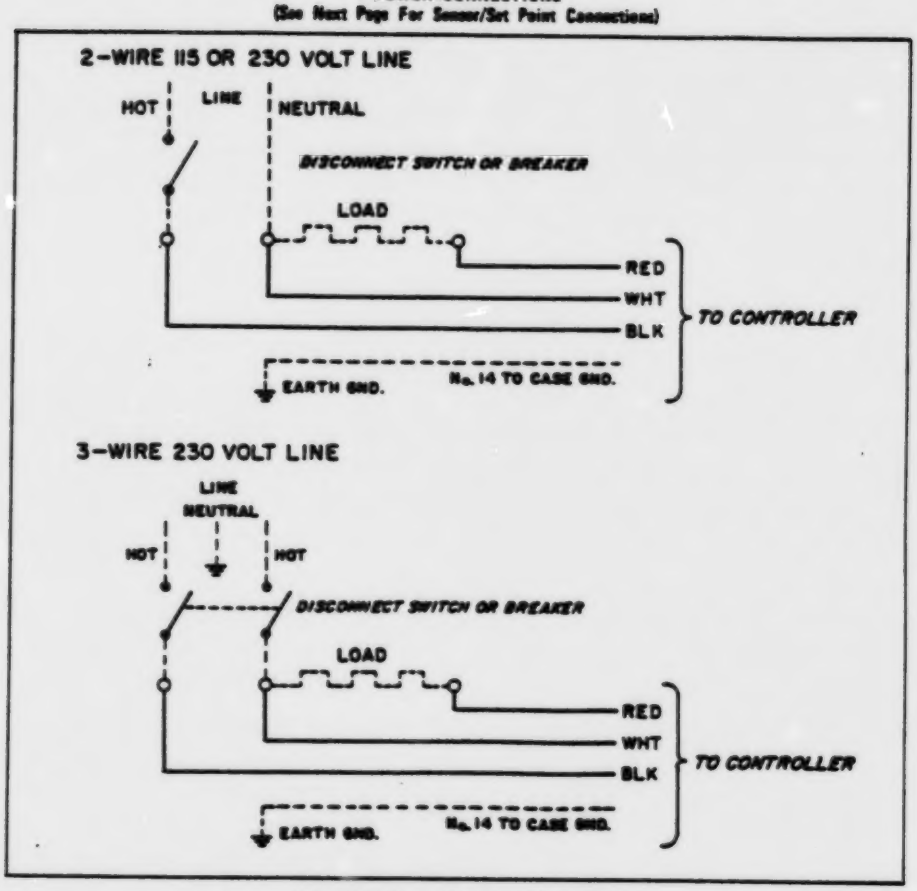
• • • CAUTION • • •

Improper connections may cause damage to the controller or sensor.

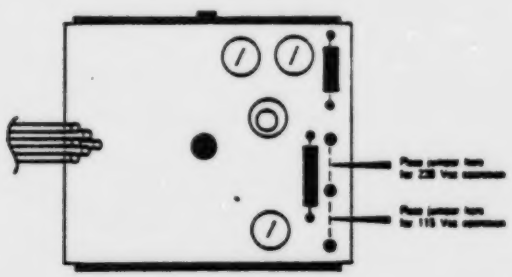
When the controller is connected to the line hazardous potential may be present on the controller, sensor, external set point control, load and any accessory apparatus. The controller case must be connected to a suitable earth ground using #14 or larger wire. Use suitably rated conductors for connecting controller and load to the line - #14 or larger wire.

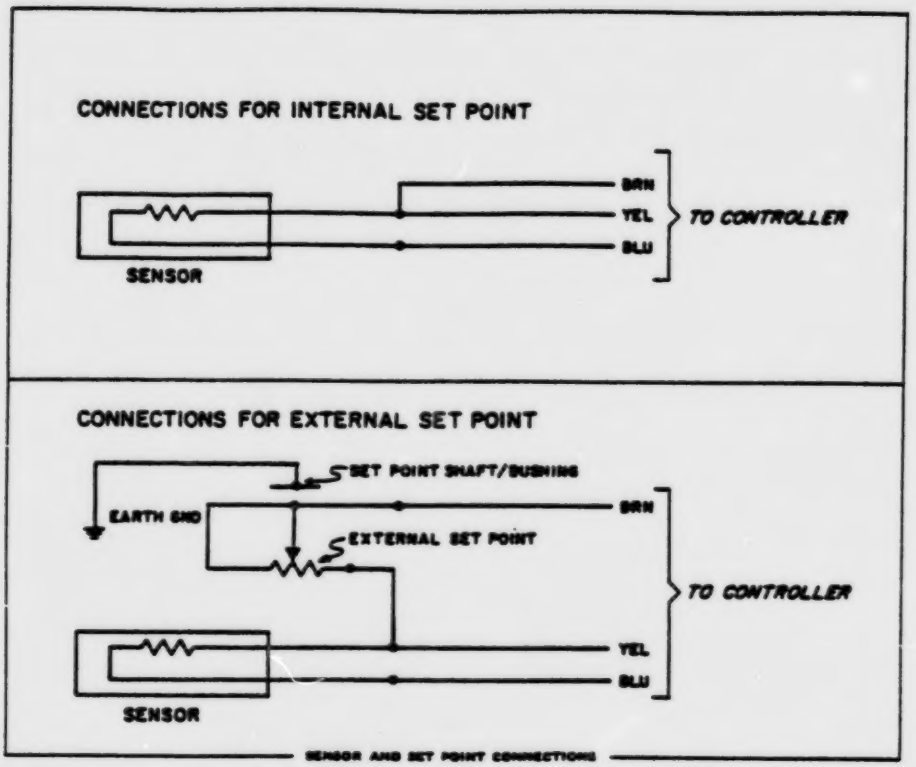
POWER CONNECTIONS

(See Next Page For Sensor/Set Point Connections)



LOCATION OF LINE VOLTAGE JUMPERS





SENSOR AND SET POINT CONNECTIONS

WARRANTY

The Model 70A Temperature Controller carries a warranty of 12 months from date of delivery for replacement of any part, except sensors, which fails during normal operation. Controllers damaged due to improper installation are not covered under this warranty. A warranty registration card is included with each unit shipped. If this card is not returned to RFL Industries, proof of purchase must accompany all controllers returned for warranty repairs. Please include a full description of the failure, and under what conditions it failed.

RFL Industries, Inc.
THERMOCONTROL DIVISION • Boonton, New Jersey 07005
Tel. (201) 334-2900 / TWX: 710-987-8362 / Cable RADARCO, N.J.